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Multifunction Interferometry using the Electron Mobility Visibility and Mean Free Path Relationship

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Abstract: A conventional Michelson interferometer is modified and used to form the various types of interferometers. The basic system consists of a conventional Michelson interferometer with silicon-graphene-gold embedded between layers on the ports. When light from the monochromatic source is input into the system via the input port (silicon waveguide), the change in optical path difference of light traveling in the stacked layers introduces the change in the optical phase, which affects to the electron mean free path within the gold layer, induces the change in the overall electron mobility can be seen by the interferometer output visibility. Further plasmonic waves are introduced on the graphene thin film and the electron mobility occurred within the gold layer, in which the light-electron energy conversion in terms of the electron mobility can be observed, the gold layer length is 100 nm. The measurement resolution in terms of the optical path difference (OPD) of ~50 nm is achieved. In applications, the outputs of the drop port device of the modified Michelson interferometer can be arranged by the different detectors, where the polarized light outputs, the photon outputs, the electron spin outputs can be obtained by the interference fringe visibility, mobility visibility and the spin up-down splitting output energies. The modified Michelson interferometer theory and the detection schemes are given in details.

Keywords: Multifunction interferometry; Electro optic sensors; Interferometric sensors, Electron mobility

1. Introduction

Measurement is the perception projection of the object that gives the observation information for the society, which can be performed by the measurement instruments. One of the instrument known as an interferometer has also been widely used and well-established years ago [Shoemaker et al., 1991;], since then there are many types of interferometers constructed and used. Generally, the interferometry has also been employed in many areas of applications [Feng et al. 2011; Morrill et al., 2010; Li et al, 2016; Szuatakowski and Palka, 2005; Bartoli et al., 2014; Gan and Batoli, 2011; Dyer et al., 2016] such as sensors, signal processing, communication, medicine, drug delivery. To date, the interferences of the small scale and the large system such as the squeezed photon up to the gravity wave were constructed by the interferometer [Coyne D.,1999, April; Steinlenchner, 2013; Weir et al, 1992; Graydon, 2012; Feng et al. 2011; Morrill et al., 2010; Li et al, 2016], where the quantum interferometer has also been reported in both theoretical and experimental works, in which the wave-particle properties have been formulated, in which their interactions within the interferometer formed and detected. Many works of the interferometers have been employed since the Weiss prototype announced [Shoemaker et al., 1991], however, there are still some problems to solve, therefore, the searching of the new interferometric systems is continued by the available new materials and detection techniques. Recently, one of the interesting works in plasmonic concept is very promising [Yan et al., 2012; Yeung et al., 2013; Ju et al., 2011, Genevet, P. et al., 2015] , whereby using the integrated layer consists of the attacked silicon-graphene-gold layers [Pornsuwancharoen et al., 2017(a), 2017(b),], in which the micro-current source could be performed by the light-electron energy conversion within the nonlinear Panda ring resonator via the whispering gallery mode. The use of graphene material to produce the plasmon wave in the interesting aspect, which can be found in many works [Smolyaninov, et al., 2005; Gumbs et al., 2016; Thomas et al, 2017; Mahigir et al., 2015], especially, with the interferometry applications [Morrill et al., 2010; Bartoli et al., 2014; Gan and Batoli, 2011] . In this work, we have proposed that the light-electron energy conversion within the stack layers can produce the change between the electron drift velocity caused by the driven group velocity in silicon to the plasmon waves in graphene, which leads the effect the output interferometer, is the mobility visibility, therefore, if there is any change in the electron mean free path will affect the change in the balanced interferometer position, which can be recovered by the recovery arm adjustment in terms of optical path difference(OPD), which can be applied by the driven external parameters9equipment) at the recovery arm. In Figure 1, the electron mobility in gold on the sensing arm can be changed by the change in a gold layer length by the external physical parameters such as current, voltage, heat etc., which can be recovered by scanning the reference arm and seen on the mobility visibility when the balanced mobility visibility is obtained. From which the scanning range in terms of the mobility path difference (Δl) is measured, which is related to the electron mobility or mean free paths. Principally, the electrical mobility(μ) is a value directly related to electrical conductivity which is given by $\mu = \frac{e\tau}{m} = \frac{ed}{mv_F}$ [Bourke and Chantler, 2010; Gall, 2016], where e is the electron charge, τ is the mean free time, m is the mass, d is the mean free paths, and v_F is the Fermi velocity of the charge carrier. The Fermi velocity can easily be derived from the Fermi energy via the non-relativistic kinetic energy equation. However, the gold film thickness can be smaller than the predicted mean free paths, making surface scattering much more noticeable, effectively increasing the resistivity. The values of the electron mean free path in various materials are also found in the reference [Bourke and Chantler, 2010; Gall, 2016].

This work proposes a novel scheme of the multifunction interferometer by using the nonlinear microring resonator known as a Panda ring resonator, where there are two major parts of the device that give the superior to the other micro-interferometers, which (i) is the two nonlinear side rings that introduce the nonlinear effect coupled into the center ring, make the required narrow output pulse width needed to obtain, which is useful for the interferometer resolution improvement, (ii) is the stacked layers of silicon-graphene-gold when light is input into the silicon layer, it can give the relationship between electron and light energy conversion, which can be useful for many applications, from which the detection of the output in the forms of light, electron and photon energy can be arranged. The novelty of this work is given as the following details, (i) the plasmonic interferometer is firstly designed and simulated by a plasmonic add-drop filter, which is a simple one comparing to the conventional Michelson interferometer, (ii) the fringe visibility resolution in terms of optical path difference (or mean free path) of 50 nm is obtained, (ii) the electron mean free path of electrons in the gold materials can be investigated by the plasmonic interferometer, (iv) this type of interferometer can be used for the applications based on the excited physical environments such as current, heat, pressure, mean free path, etc. Bio-sensor is also available, for example, when the embedded layers are covered by the bio-cells, therefore, if there is any change on the gold layer induced by the bio-cells activities, then the recovery can be done by the proposed interferometer and required parameters measured. The other types of the interferometers such as conventional, plasmonic and quantum (polarized light, photons and spins) interferometers are also available by the different detection arrangements.

2. Theoretical Background

When the input light power from a monochromatic light source is input into the stacked layer via a silicon layer, the light energy is transferred to graphene and gold by the plasmon waves, from which the light-electron energy conversion is formed. By using the relationship $V_d = \mu E$, is the magnitude of the electron drift velocity caused by the electric field, E is the electric field magnitude applied to a material, and μ is electron mobility of the material. The light intensity(I) is the electrical field€ projected on the photo-detector, is given by $I \propto E^2 = \left({}^{V_d}/_{\mu}\right)^2$. In this work, the electron drift velocity in the studied material (gold) is modulated by the plasmon waves from silicon to graphene as shown in Figure 1. The driven electron driven mobility is obtained by the driven group velocity injected by the silicon-graphene plasmonic waves [Pronsuwancharoen et al. 2017(a), 2017(b)], which provides the increase in overall electron mobility, therefore the irradiance output at the detector as the function of the recovery arm (optical path difference, Δl) of the Michelson interferometer, can be seen in the form of the interference fringe (mobility visibility) by scanning the recovery sensing arm, which is the reference arm. The relationship of the interference fringe in terms of the mobility visibility of the plasmonic interferometer can be written by [Szuatakowski and Palka, 2005].

$$\mathrm{I}\,(\Delta \boldsymbol{l}) = \boldsymbol{I_0}\left(\boldsymbol{k_{12}^2 k_{22}^2 r_A^2 + k_{13}^2 k_{32}^2 r_B^2}\right)\left[\mathbf{1} + \boldsymbol{V}(\Delta \boldsymbol{l})\boldsymbol{cos}\left(\mathbf{2}\frac{\mathbf{2}\boldsymbol{\pi}}{\boldsymbol{\lambda_0}}\,\boldsymbol{N}[\boldsymbol{D} - \Delta \boldsymbol{l}(\mathbf{1} - \boldsymbol{p_e})]\right)\right] \qquad \mathbf{1}$$

Where $\boldsymbol{I}$ is the output irradiance (Mobility), V is the contrast of the interferometer, D is the arm length difference (optical path difference, OPD), $\boldsymbol{I_0}$ is the input source irradiance (Mobility), N is the effective refractive index of the waveguide, λ_0 is the light source wavelength, p_e= 0.22 is the elastic coefficient of the waveguide, k_{ij} are the coupling coefficients,r_A, r_B: Reflection coefficients of the waveguide ends. In this case, Δl is also additionally obtained from the right and left two side rings in terms of the phase differences.

3. Simulation Results

Before the simulation, the preliminary result of the system was investigated by using the selected parameters as shown in Figures 2 and 3. The used simulation tools are the commercial Opti-wave and MATLAB programs. The simulation was taken after the confirmed results by graphical results from the Opti-wave. All parameters are given in the Figure caption. In a simulation, the interferometer output mobility visibility can be obtained by the suitable parameters in an Equation (1), where the change of the parameters from light intensity to be the output mobility is given in the previous paragraph. The selected parameters are given in the Figure captions. In operation, light from a source with the input power of 1.0 mW at the center wavelength of 1.55 µm is input into the system via a silicon waveguide, which has the waveguide loss of 0.1 dB$\boldsymbol{mm^{-1}}$, the other parameters are given in the Figure caption. In Figure 4, the relationship between the electron mobility and gold layer length is investigated and plotted, which is found that the suitable length is 100 nm when the input power is at 1.0 mW, which will be used to form the interferometer measurement range and resolution in this investigation. In Figure 5, plot ($\Delta \boldsymbol{l}$) and the change in mean free paths, µ= $\boldsymbol{\frac{e\tau}{m}} = \boldsymbol{\frac{ed}{mv_F}}$, where $\boldsymbol{V_F} = 10^5\ \mathrm{ms}^{-1}$ of electron in gold [Bourke and Chantler, 2010; Gall, 2016], the electron mobility in gold is 42.6 cm^2 V^{-1} s^{-1}, the input power is fixed at 1.0 mW, the electron mass = 9.10 × 10^{-31} kilograms, the electron charge = 1.60 × 10^{-19} coulombs. The refractive indices of a silicon and GaAsInP/P are 1.46 and 3.14, respectively. The fringe peak to peak is obtained at $\Delta \mathbf{t} \sim$ 2.5 fs, is ~0.5 x10^{-7}m or ~100 nm, where (a) color, (b) black and white signals drop the through and drop ports, respectively. The peak to peak of the optical path difference of the interferometer is plotted in set figures, which is $\sim$ 50 nm. Principally, the resolution can be improved by adjusting the two side ring parameters, for an instant, the pulse width in terms of time can be as(attosecond), which can lead to obtaining the OPD resolution of 0.1 nm, however, the system may be facing the other critical issues, for example, the small vibration and temperature changing effects. The plasmonic interferometer is formed by applying the stacked layers on the conventional Michelson interferometer, where in this case we assume that the change in the gold layer length is not larger than the elongation limit. The contrast of the interferometer output in an equation can be given by [Szuatakowski and Palka, 2005].

$$(\Delta \boldsymbol{l}) \ \frac{= \boldsymbol{k_{12}k_{22}r_A k_{13}k_{32}r_B}}{\boldsymbol{k_{12}^2 k_{22}^2 r_A^2 k_{13}^2 k_{32}^2 r_B^2}}\left(\textstyle\sum_{q=1}^{p} \boldsymbol{H_q}\right)^{-1} \mathbf{.\ exp}\left[-\left(\frac{\boldsymbol{\pi N}}{\sqrt{\ln 2}}\frac{\Delta\boldsymbol{\lambda}}{\boldsymbol{\lambda_0^2}}[\boldsymbol{D} - \Delta \boldsymbol{l}(\mathbf{1} - \boldsymbol{p_e})]\right)^2\right] \qquad \mathbf{2}$$

$$\mathbf{x}\sqrt{\left(\textstyle\sum_{q=1}^{p} \boldsymbol{H_q}\ \mathbf{cos}(\boldsymbol{A})\right)^2 + \left(\textstyle\sum_{q=1}^{p} \boldsymbol{H_q sin}(\boldsymbol{A})\right)^2}$$

Where A = $\left(\mathbf{2}\frac{\mathbf{2\pi}}{\boldsymbol{\lambda_0}^{\mathbf{2}}}\boldsymbol{\Delta\lambda_1}\ (\boldsymbol{q}-\mathbf{1})\boldsymbol{N}[\boldsymbol{D}-\boldsymbol{\Delta l}(\mathbf{1}-\boldsymbol{p_e})]\right)$, λ_0 is the input source wavelength, $\Delta\lambda$ is the spectral width, $\Delta\lambda_1$ is the mode spacing, H_q is the amplitude of the q^{th} of the output mobility mode and D is the initial interferometer arm length difference.

In Figure 5(b), there are 2 groups of the interference fringes seen, are obtained from the center ring, and two side rings, respectively. In this case, the time difference signals between the two side rings, right and left rings, induce the interference fringes occurring alongside with the center ring. The through port resonant signals are seen at 280 fs when the drop port signals are at ~280 and ~380 fs. From which the delay time between the first and second resonance occurrence is ~100 fs. However, the drop port signals are detected but they are submerged by the through port signals at the center. When the signals in the center ring are at the resonance, the interferometer can be operated and the required measurement performed. The second resonance is seen at ~ 100 fs apart from the first one, with the clearly fringe patterns with the two side rings. Apart from the phase modulation, the two side rings can offer the self-calibration each other, for an instant, if the output fringe is shifted from the unexpected values from the environments, the other ring output fringes can be used to confirm the actual values, which is the comparative calibration. Moreover, one side ring can be placed as a sensing unit, while the other one is fixed to be the reference unit, which is the similar application to the sensing and recovery arms of the interferometer. But in this case, there is the ring surface area can be placed by the sample, for an instant, a drop of liquid or cells, from which the suitable function of the proposed interferometer can be accommodated and performed the measurement.

Further applications can be employed, where firstly the interferometer output visibility contrast can be adjusted by the selected parameters in an Equation (2), in which the interference fringes of the imbalanced interferometer positions can be more clearly recovered and the OPD measured. However, the contrast is not the necessary requirement if the resolution of the OPD is acceptable. Secondly, at the interferometer output (drop port output), the different detection equipment can be arranged by the 3 types as given in Figure 2, where (i) the output light (interference fringes), (ii) the polarized light and entangle arrangement, (iii) the spin up-down detection or the sensing schemes can be configured by using the photo-detector, photon counter and magnetic sensor for light intensity, photons and spin energy, respectively. From which, the output light at the drop port can provide the polarization information, which can be used to form the entangled polarized light, which is useful for the quantum sensor and cryptography. The polarized light components are the vertical and horizontal $\langle\boldsymbol{V}|\boldsymbol{H}\rangle$components. The electron splitting unit and the magnetic sensors can be applied to measure the spin up and down energies, which can be used to form the digital code “0” and “1” by the spins “Up” and “Down”, while the spin entanglement and sensors can also be arranged. The spin up and down energies are $+\hbar/\mathbf{2}$ and $-\hbar/\mathbf{2}$, where they represented by $\langle\boldsymbol{\sigma}^{+}|\boldsymbol{\sigma}\text{-}\rangle$ [Fujikura and Shrock, 1980].

4. Conclusion

We have proposed the novel work of the multifunction interferometer using the nonlinear microring resonator with the embedded between silicon-graphene-gold layers on the device tips. The input of the system via the input port can be the injected light from the laser source or applied current and light, in which the coupling between electron and light energy will affect the system output and being observed at the drop port detector. If there is any change on the sensing unit will be recovered by the recovery arm adjustment and the measurement is obtained by the matching between the balanced mobility visibility and the OPD of the recovery arm. The significant information is a relationship between electron and light energy can be obtained, and the interpretations in terms of the mean free path (or OPD) and mobility visibility is achieved. The measurement range of ~ 50 nm can be achieved, while the linear relationship between the output mobility and gold length is preserved. This is the simulation work, however, all device parameters were used respecting to the current fabrication technology and the citations were given. The theoretical description is given with the new arrangements for the plasmonic interferometer. However, all interferometers can be used and described by the same equation.

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Figure Captions:

Figure 1: A schematic of the modified optical add -drop filer with the silicon-graphene-gold embedded arms, where E_{in}: input port optical field, E_{th}: optical field at throughput port, E_{drop}: optical field at drop port,E_{add} : optical field at add port , R_d:center ring radius , R_r: Right ring radius and R_l: Left ring radius; κ_s: coupling constants

Figure 2: A schematic plasmonic interferometer, where are the ring radii of the center ring and two side rings, right (R_r) and left (R_l) hands. The sensing and reference arms, input and drop ports are connected by the stacked silicon-graphene-gold layers, κ_s= 0.5. There can be three detection schemes arranged as followings: (i) The photon counter for the entangled photon arrangement by is placed after the polarizing beam splitter, (ii) the split spin detection is formed by the magnetic sensors for the spin up and down energy detection. The output stacked layer is covered by the thin magnetic film for the spin splitting arrangement, (iii) the mobility output detector is placed after the polarizing beam splitter.

Figure 3: Shows the 3D Opti-wave result of the system in Figure 1 for a preliminary investigation [Srithanachai et al., 2012], the parameters are R_l=1.4 µm, R_r=1.5 µm and R_d =2.0 µm. The sensing and reference arm reflectivity is 0.10(10%), $R_l$and R_rR is adjusted as the phase modulator, the two ring material is a GaAsIn/InP, the waveguide loss is 0.5 dBmm^{-1}.

Figure 4: Plot of the gold layer mobility and the input power, the maximum power is 5.0 mW, where the change in gold layer length (L_{Au}) of the sensing arm is fixed at 100 nm. However, the good linear relationship of the gold layer length is 200 nm. The change in affects the change in the balanced position of the interferometer, the recovery OPD is required for balanced fringe visibility.

Figure 5: Plot of the mobility visibility and the change in mean free paths, µ=$\frac{e\tau}{m}$=$\frac{ed}{mV_F}$, where V_F= $10^5 ms^{-1}$ of electron in gold [Bourke and Chantler, 2010; Gall, 2016], where the mobility (input power) is fixed at 1.0 mW, the electron mass = 9.10 × 10^{-31}kilograms, the electron charge = 1.60 × 10^{-19} coulombs. The refractive index of a silicon is 1.46, GaAs = 3.66 and Au=0.61. The fringe peak to peak is obtained at $\Delta t = 2.5$ fs, is 0.5 x 10^{-7}m or 50 nm, where (a) the blue color is the through port output signals and the red color is the drop port output signals, (b) the black and white signals of Figure 5(a). The interference fringes of the interferometer are seen at the drop port.

Graphical Abstract: Plot of the mobility visibility and the change in mean free paths, µ=$\frac{e\tau}{m}$=$\frac{ed}{mV_F}$, where V_F= $10^5 ms^{-1}$ of electron in gold [Bourke and Chantler, 2010; Gall, 2016], where the mobility (input power) is fixed at 1.0 mW, the electron mass = 9.10 × 10^{-31}kilograms, the electron charge = 1.60 × 10^{-19} coulombs. The refractive index of a silicon is 1.46, GaAs = 3.66 and Au=0.61. The fringe peak to peak is obtained at $\Delta t = 2.5$ fs, is 0.5 x 10^{-7}m or 50 nm, where (a) the blue color is the through port output signals and the red color is the drop port output signals, (b) the black and white signals of Figure 5(a). The interference fringes of the interferometer are seen at the drop port.