3D-fringe pattern coding and recognition using plasmonic sensing circuit

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Abstract: 3D interference fringe pattern recognition using a plasmonic sensing circuit is proposed. The plasmonic sensing in the form of a panda ring comprises an embedded gold grating at the microring center. WGM (whispering gallery mode) is observed at the microring center with suitable parameters. The dark soliton of 1.50µm wavelength excites the gold grating which leads to electron cloud oscillation and forms the electron densities where the trapped electrons inside the silicon microring are transported via wireless connection using WGM and cable connection. The spin-down \( |\downarrow\rangle (|1\rangle) \) and spin-up \( |\uparrow\rangle (|0\rangle) \) result from the electron cloud oscillation. By using the changes in gold lengths, the excited electron pattern recognition can be manipulated, where the values "0 and "1" are useful for pattern recognition. The fringe patterns of the plasmonic interferometric sensor are recorded, which means that the novel 3D pattern recognition can be possibly implemented and used in many applications. Therefore, the plasmonic sensing circuit can be used to form the quantum code, quantum encryption, quantum sensor, and pattern recognition.

Keywords: Plasmonic circuit; Quantum interference; Fringe pattern; 3D pattern recognition; Gold grating

1. Introduction

Pattern recognition involves the observation and recognition of regularities in a data set, which is generally classified according to the procedure or method used in generating the patterns. In other words, it involves recognizing patterns in data automatically by using pattern recognition systems. Pattern recognition systems use different mathematical models and algorithms in recognizing patterns in data sets. Several researchers have developed different pattern recognition systems that have been applied in recognizing patterns in different data sets (Soliman et al. 2018; Si and Yan 2015; Zhaoxu and Xiaodong 2013; Hong et al. 2019; Kumar 2016; Bakhtiar and Hosseinzadeh 2016; Salehi and Dehyadegari 2016; Kumar et al. 2019; Farrokhi et al. 2015; Kotb and Guo 2019; Morsy and Alsayyari 2019; Maity et al. 2016; Metja and Janyani 2015; Jardovic-Pavlovic et al. 2020; Liu et al. 2016; Imtiaz et al. 2020; Mu et al. 2019; Bhnassy et al. 2019).

Motivated by the above-mentioned works, this present work has proposed a pattern recognition system. The principle behind the operation of the pattern recognition system is the space-time function. The pattern recognition system consists of a plasmonic sensing circuit. The plasmonic sensing circuit which is in the form of a panda ring comprises gold gratings embedded at the microring center and is useful for wide applications due to the nonlinear effect it exhibits. The plasmonic sensing circuit is employed for the construction and recognition of 3D fringe patterns that result from the interference of the input light of the circuit. Interference fringe patterns involve the merging of two or more sources of light and these patterns have valuable information for various applications. The interference fringe can also be formed when two light waves of the same phase, frequency, and amplitude respectively meet at a point and are superimposed. To produce interference fringe patterns different instruments are used for this purpose. One such instrument is the interferometer, which comes in different shapes and sizes, but the main working principle is the interference of light from different sources to produce the interference fringe patterns (Kowsari and Saghaei 2018). There are two main kinds of interferometer namely classical and quantum interferometer. Classical interferometer makes use of classical resources to...
produce classical interference fringe while quantum interferometer makes use of quantum resources to produce quantum interference fringe. The plasmonic sensing circuit in this present work has been employed for 3D quantum interferometer (Arumona et al. 2020). In a simulation, two programs are employed. Firstly, for simulating the plasmonic sensing circuit and the observation of the whispering gallery mode (WGM) the OptiFDTD software is used. Secondly, extracted parameters from the OptiFDTD results are used by the Matlab program to simulate 3D interference fringe and the results have been interpreted for 3D interference fringe pattern recognition.

2. Background
The 3D pattern recognition system is given in Figure 1, where the plasmonic sensor is formed by a gold grating driven by a space function. The input source is a soliton pulse, from which the electron cloud is generated by the whispering gallery mode (WGM), which transport in the circuit. The transport electrons can be controlled by the space-time input function. The change in electron cloud densities can transfer to plasmonic sensors and transported electron clouds, which can be applied for pattern recognition using the interference fringes related to the electron transport projections.

The input source is the space function called a dark soliton pulse, given by an equation (1) (Agrawal 2011).

$$E_{in} = \overline{B} . Tanh \left( \frac{T}{T_0} \right) \exp \left( \frac{z}{2L_0} \right)$$

The dark soliton pulse forms the input light of the circuit where in equation (1), $\overline{B}$, $z$, $T_0$, $L_0$, and $T$ are the amplitude of the input light, propagation distance, initial time of the soliton pulse, length dispersion, and final time of the soliton pulse respectively.

At the add port ($E_{add}$) port of the pattern recognition, the input light multiplex with the time function is multiplexed by the space-time function signal, which is employed to form the spin projection given by an equation (2).

$$E_{add} = D . e^{\pm i \omega t}$$

where in equation (2) the $e^{\pm i \omega t}$ is the control time and $\pm$ signs indicate full-time slot axis. The pattern recognition system generates fringe patterns by means of interference of the input light as described by an equation (3) as (Szuatakowski and Palka 2005), and the fringe contrast ($V(\Delta I)$) is given in an equation (4).

$$I(\Delta I) = I_0 \left[ k_{11}^2 k_{22}^2 + k_{12}^2 k_{21}^2 \right] \left[ 1 + V(\Delta I) \cos \left( \frac{4\pi}{\lambda_0} N \left[ D - \Delta I (1 - p_e) \right] \right) \right]$$

$$V(\Delta I) = \frac{k_{11}^2 k_{22}^2 r_A^2 r_B^2 k_{12}^2 k_{21}^2}{k_{12}^2 k_{22}^2 + k_{12}^2 k_{21}^2} \left( \sum_{q=1}^{p} H_q \right)^{-1}$$

$$\times \exp \left[ -\left( \frac{\pi N}{\sqrt{\ln 2}} \frac{\Delta \lambda}{\lambda_0^2} \left[ D - \Delta I (1 - p_e) \right] \right)^2 \right]$$

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

where $I$, $I_0$, $p_e$, $N$, $\lambda_0$, $r_A$, $r_B$, $D$, $V(\Delta I)$, and $k_{ij}$, are the output irradiance, input source irradiance, waveguide elastic coefficient, waveguide effective refractive index, wavelength of light source, waveguide end reflection coefficients, arm length difference, fringe contrast, and amplitude coefficients, $i$, $j$ =1, 2, 3, respectively.

$$A = \frac{4\pi}{\lambda_0^2} (q-1) N \left[ D - \Delta I (1 - p_e) \right]$$

$\Delta \lambda$, $H_q$, and $\Delta \lambda$ are the mode spacing, mode amplitude and spectral width respectively.

The Drude model (Tunsiri et al. 2019) describes the behavior of the electrons in the gold grating as given in equations (5) and (6) as:
\[ \varepsilon(\omega) = 1 - \frac{ne^2}{\varepsilon_\infty m\omega^2} \]

where \( \varepsilon_\infty \), \( n \), \( m \), \( e \) and \( \omega \) are relative permittivity, electron density, electron mass, electron charge and angular frequency.

At resonance, angular frequency becomes plasma frequency given as:

\[ \omega_p = \left( \frac{ne^2}{\varepsilon_\infty m} \right)^{\frac{1}{2}} \]

From an equation (6) the electron density \( n = \frac{\omega_p^2}{e^2} \varepsilon_\infty m \), the output fields of the pattern recognition system are described as (Prateep et al. 2016)

\[ E_{th} = m_2 E_{in} + m_3 E_{add} \]

\[ E_d = m_5 E_{add} + m_6 E_{in} \]

where the terms \( m_2-m_6 \) are constants in equations (7) and (8) as explained in (Prateep et al. 2016).

From the system’s output in Figure 1, the normalized intensities are written as (Pornsuwancharoen et al. 2017)

\[ \frac{I_{th}}{I_{in}} = \left( \frac{E_{th}}{E_{in}} \right)^2 \]

\[ \frac{I_{d}}{I_{in}} = \left( \frac{E_d}{E_{in}} \right)^2 \]

The nonlinearity also known as Kerr effect exists throughout the system and is included in the \( n = n_0 + n_2 I/n_0 + n_2 P/A_{eff} \) equation, where \( n \), \( n_0 \), \( n_2 \), \( I \), \( P \) and \( A_{eff} \) are refractive index, linear refractive index, nonlinear refractive index, optical intensity and effective core area, respectively. The Bragg wavelength \( \lambda_B = 2n_e \Lambda \), where \( \Lambda \) and \( n_e \) are grating period and gold grating’s effective refractive index.

**Figure 1:** The 3D pattern recognition system, where (a) fabrication system, where nonlinear phase modulator is labelled NLM. The microring center has embedded gold gratings. The reference and sensing arm tips have gold layer, (b) sensor circuit, where \( E_{in} \) (input port), \( E_{add} \) (add port), \( E_d \) (drop port) and \( E_{th} \) (throughput port), microring center radius is labelled Rd, small ring radii are labelled RL and RR are the side ring radii, while coupling constants (\( K_1-K_4 \)). The other parameters are given in Table 1. The feedback is protected by applying the isolator.
3. Results and Discussion

The OptiFDTD and Matlab programs were used for the simulation. The OptiFDTD of version 12.0 (OptiFDTD 2019) is firstly used for simulating the fabricated system as shown in Figure 1(a). The input light (dark soliton) of 1.50µm wavelength enters the system via the input port as given in equation (1) and the system outputs are described in equations (7 and 8). The small side rings also known as the phase modulators induce the nonlinearity effect in the plasmonic sensing system and the WGM is observed at the microring center with optimized parameters in Table 1 as shown in Figure 2. The nonlinearity effect enables the trapping of light at the microring center. The number of time steps employed in simulation is 20,000, which was applied for the resonant condition. The embedded gold gratings produce the Bragg wavelength when polaritons induced by the gratings lead to dipole oscillations. The Matlab program uses the extracted parameters from the OptiFDTD results as a second step in simulating the 3D fringe pattern. The schematic diagram in Figure 1(b) outlines the process involved in the 3D interference fringe pattern construction. The spin up \(|↑\rangle\ (|0\rangle\rangle)\) with the spin matrix \(\frac{\hbar}{2} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\), and spin down \(|↓\rangle\ (|1\rangle\rangle)\) with the spin matrix \(\frac{\hbar}{2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\) of electrons results when the gold gratings are illuminated by the input light where the electron density \([n = \frac{ω^2}{ε_0} ε_0 n]\) is formed by the electron cloud oscillations. In manipulation, the change in the trapped electron density is formed by changing the gold sensing arm length.

The length of the gold layer at the tip of the reference arm is fixed while for the tip of the sensing arm it is varied. The space signal is multiplexed with time at the add port to produce the space-time function as written in an equation (2), in which the electron spin projection can be applied. The interference fringe is formed by the reflected and sensing arms, which is described in an equation (3). When the length of the gold layer is changed at the sensing arm, it changes the detector’s output as written in equations (9 and 10). The final output is detected at the drop port, where the spin-down and spin-up of the trapped electrons are the projections from the x-y, x-z and y-z planes, respectively. The trapped electron is transported along the z-axis, which is lead to the construction of the 3D interference fringe pattern. By using the space-time control, the required spin projection can be obtained. Figure 3(a)-(c) is the 3D interference fringe pattern for three different gold lengths of 100 nm, 200 nm, and 300 nm where the obtained codes can form the pattern recognitions. The interaction between electrons and exciting stimuli in the plasmonic sensor can generate the interference fringes (patterns) shown in Figures 3 and 4. The physical point of view is the generated 3D-fringe patterns which form the quantum codes.

![Figure 2](image-url)

Figure 2: Plot of the Opti-wave results, where the whispering gallery mode is formed by using suitable parameters as given in Table 1, where (a) the optical intensity, (b) electric field distribution.
(spin up and spin down of electrons), where the patterns in the quantum codes are recognized by the plasmonic sensing scheme. The quantum codes in the x-y, x-z and y-z planes are shown in Table 2. The specific codes of the 3D electron spin projections can be formed. The spin-up is 0 and spin down is 1. The transporting electrons can be configured as no code, which leads to having the triple codes as [0, -, 1]. The sign “−” represents the code of transmitted electrons without the projection.

Figure 3: The 3D interference fringe plot for (a) 100nm gold length (b) 2000nm gold length (c) 300nm gold length
Figure 4: The 3D interference fringe plot for 100-1000 nm gold lengths

Table 1: The optimized simulation parameters (Pornsuwancharoen et al., 2017; Prabhu et al., 2010; Blaber et al., 2009)

| Parameters                                      | Values        | Units        |
|------------------------------------------------|---------------|--------------|
| Input power (P)                                 | 20            | mW           |
| Length of silicon linear waveguide (L)          | 15.0          | µm           |
| Si microring center radius (Rd)                  | 3.0           | µm           |
| Left small-ring radius (RL)                     | 1.0           | µm           |
| Right small-ring radius (RR)                    | 1.0           | µm           |
| Au dielectric constant (ε_o)                    | 6.9           |              |
| Gold permittivity (ε)                           | 10.0          |              |
| Gold layer length (La)                          | 100-1000      | nm           |
| Width of Au grating (W_{Au})                    | 0.4           | µm           |
| Thickness of Au grating (d)                     | 0.2           | µm           |
| Length of Au grating (L_{Au})                   | 1.6           | µm           |
| Amplitude Mode (H_{o})                          | 1.0           |              |
| Coupling coefficient (K)                        | 0.7-1.0       |              |
| Loss of insertion (γ')                          | 0.5           |              |
| Au refractive index (n)                         | 1.8           |              |
| Amplitude coefficient (k_{ij})                  | 0.01          |              |
| Si refractive index (n_{Si})                    | 3.42          |              |
| Reflection coefficient (r_{a, b})               | 0.5           |              |
| Elastic coefficient (p_e)                       | 0.22          |              |
| Si refractive index nonlinear (n_{z})           | 1.3x10^{-13}  | m²W⁻¹        |
| Input light wavelength (λ_{i})                  | 1.50          | µm           |
| Waveguide core effective (A_{eff})              | 0.30          | µm²          |
| Waveguide loss (α)                              | 0.50          | dB.(cm)⁻¹    |
| Plasma frequency (ω_{p})                        | 1.2990x10^{16} | radsec⁻¹    |
| Electron mass (m)                               | 9.11x10^{-31} | kg           |
| Electron charge (e)                             | 1.6x10^{-19}  | Coulomb      |
| Permittivity of free space (ε_{o})              | 8.85x10^{-12} | Fm⁻¹         |
| Reduced Planck’s constant (h)                   | 1.00          | ARU          |
Table 2: Results of the quantum codes obtained from the interference fringe patterns in Figure 3.

| Figures | Gold Length (nm) | Directions | Pattern recognition codes |
|---------|------------------|------------|--------------------------|
| 3(a)    | 100              | x-y        | [0101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101] |
|         |                  | x-z        | [10110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110] |
|         |                  | y-z        | [00100100100100010001000100100100100100100100100100100100100100100100100100100100100100100100100100100100100100100] |
| 3(b)    | 200              | x-y        | [0101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101] |
|         |                  | x-z        | [10110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110] |
|         |                  | y-z        | 0110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110 |
|         |                  |            | [00100100100100010001000100100100100100100100100100100100100100100100100100100100100100100100100100100100100100100] |
| 3(c)    | 300              | x-y        | [0101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101010101] |
|         |                  | x-z        | [10110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110] |
|         |                  | y-z        | 0110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110110 |
|         |                  |            | [00100100100100010001000100100100100100100100100100100100100100100100100100100100100100100100100100100100100100100] |

4. Conclusion
A plasmonic sensing circuit for the construction of a 3D interference fringe pattern is proposed. WGM is generated and excited by the embedded gold gratings at the microring center. The trapped electrons are excited and interfered by the applied stimuli. The plasmonic sensing circuit produced the transport electron cloud that can be applied to form the quantum interference based on the Michelson interferometer. The interference fringes are formed by the reflected sensing and reference arms, from which the fringe patterns can be formed by the trapped electron interference and detected at the detector. The 3D interference fringes are constructed from the trapped electron spin-down $|\downarrow\rangle (|1\rangle)$ in the x-axis and spin-up $|\uparrow\rangle (|0\rangle)$ in the y-axis, respectively, while the trapped electrons propagate in the z-axis. In application, a proposed circuit can be applied to pattern any form of disturbances, which can be coded and used for pattern recognition and recovery. Moreover, the high-density quantum codes known as quantum cellular automata (QCA) can also be applied by the proposed circuit, where the changes in the electron cloud spins can be identified and specific codes obtained.

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