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Numerical investigation of graphene-based metamaterial microstrip radiating structure

Vigneswaran Dhasarathan¹⁻², Nizam Bilakhiya¹, Juveriya Parmar³, Mayurkumar Ladumor⁴ and Shobhit K Patel¹⁻２⁻⁶

¹ Division of Computational Physics, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam
² Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
³ Electronics and Communication Department, Marwadi Education Foundation’s Groups Of Institutions, Rajkot, 360003, India
⁴ Physics Department, Marwadi University, Rajkot, 360003, India
⁵ Electrical and Computer Engineering Department, University of Nebraska-Lincoln, Lincoln NE, 68588, United States of America
⁶ Author to whom any correspondence should be addressed.

E-mail: vigneswaran.d@tdtu.edu.vn and shobhitkumar.patel@marwadiesucation.edu.in

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Abstract
Recent advancement in antenna technology is directed to achieve reconfiguration of radiating structure parameters. In this paper, we propose graphene-based reconfigurable and high gain microstrip radiating structure for multiband wireless communication applications. The circular copper patch is used as a radiating element of the radiating structure. Graphene layer with circular holes is applied to this microstrip based radiating structure to tune the radiating structure parameters. The radiating structure is stacked with superstrate layers to improve the gain of the design. Frequency reconfiguration and gain enhancement are achieved by varying the chemical potential of graphene. Radiating structure analysis in terms of the reflection coefficient, radiation pattern and gain polar plot is obtained. The proposed reconfigurable radiating structure can be used for L and S-band applications.

1. Introduction

An radiating structure (antenna) is defined as a metallic device for radiating or receiving radio waves. The radiating structure can transmit as well as receive signals and it is also a transducer which converts electrical signals to electromagnetic signals or vice-versa [1]. Radiating structure plays an important role in the operation of all communication devices. It is used in wireless local area networks, mobile telephony, satellite communication, and cognitive radio [2]. Thin and flexible radiating structure design based on silver nanoparticles on PET substrate is analyzed in terms of the reflection coefficient, VSWR and gain radiation pattern [3]. Reconfiguration is very important nowadays because of switching of antenna frequency from one point to the other. Research in antenna reconfiguration in terms of frequency and gain is mostly obtained with PIN diode or MEMS switching mechanism. It is complex to design and fabricate conventional reconfigurable antennas based on switches [4].

Graphene is a unique material having excellent electrical properties and optical properties. These excellent properties can be mixed with antenna properties to achieve reconfiguration ability. Graphene-based reconfigurable antenna simplifies the fabrication process of reconfigurable antennas as frequency tuning is achieved simply by changing the chemical potential of graphene [5]. The use of graphene in antennas could potentially lead to very interesting features such as high directivity and tuning of the spectrum [6].

Reconfigurable high impedance graphene-based surface is analyzed for different chemical potential in [7]. Graphene is basically a single atomic layer of graphite. Graphene is formed by carbon atoms arranged in a two-dimensional honeycomb crystal lattice [8]. Graphene was first demonstrated by Andre Geim and Konstantin Novoselov, from the University of Manchester, in 2004 [9]. Graphene has a unique combination of superb properties like thinnest as well as strongest. It also conducts heat better than all other materials [10]. Graphene is the most suitable material to make an antenna as it offers tunability with parameters like chemical potential, temperature and scattering rate [9]. Electromagnetic properties can be manipulated through metamaterials.

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There are various designs available with split ring resonator structure. Some of the basic structures of SRR are a single ring with one cut, single ring with two cut and SRRs with multiple splits rings. Change in electromagnetic characteristic depends on the structure of split ring [11].
Reconfigurable and high gain antennas are used widely nowadays because of its applications in radar, satellite, mobile, etc. [12–21]. Two symmetric U-slots are added in an antenna to achieve reconfiguration. This reconfigurable antenna is applicable in radar applications [12]. The reconfigurable patch antenna is presented to have polarization agility. Reconfigurability is achieved by using p-i-n diodes [13]. Pattern reconfigurable patch antenna with parasitic elements is presented in [14, 15]. The reconfigurable and high gain antenna is designed and reconfiguration is achieved by using switching. Different switching states are activated to tune the frequency and improve the gain of the antenna [16]. Corrugated split ring resonators are added to improve the gain of microstrip based antenna [17]. Lumped capacitors are added in the microstrip patch antenna to achieve reconfiguration [18]. Frequency and polarization reconfiguration are possible with the addition of split ring resonators to microstrip patch antenna [19, 20]. Multiple band frequency reconfigurations are achieved with PIN diode switches [21].

The reconfiguration is very important and required phenomenon in antennas nowadays and there are very few antennas which give broadband behaviour and frequency reconfiguration both. So we have proposed here, a

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**Figure 4.** Graphene layer having 40 mm width and length. The radius of hollow Circular shape R1 is 3 mm. Distance between the centres of the two circles is denoted by R2 having 10 mm distance. (grey colour represent the graphene layer).

**Figure 5.** 2D geometry of microstrip antenna having applied external biasing with chemical potential ($\mu_c$) to the graphene layer. Here ‘h’ represents the height of substrate, ‘g’ represents the height of the ground, ‘c’ represents the air gap between ground plane and graphene layer, ‘e’ represent the height of the copper patch. Graphene chemical potential is applied through different pads to cover the whole geometry and $V_{DC1} = V_{DCN}$.
new radiating structure design using graphene material which is targeted to achieve frequency reconfiguration and broadband behaviour both by changing the graphene chemical potential. This frequency reconfiguration can be used in many applications and is presented in section 3.
2. Design and modelling

The proposed graphene antenna is designed using a 40 mm square substrate. The FR4 material is used as a substrate with permittivity \( \varepsilon_r = 4.4 \). Figure 1 represents the design of graphene antenna along with its stack layer defining separate stack layer in the right side. Figure 2 represents the structure of 3D microstrip antenna. In figure 1 and 2, the antenna has (FR4) substrate having a length of 40 mm, the width of 40 mm and height of 0.8 mm. The height \( g \), length and width of the ground plate made of copper material is kept the same as that of the substrate material. The radius of the circular patch placed above the substrate is denoted by \( d_1 \) is 18 mm. The height which is denoted by \( c \) is 0.5 mm. The width of the feed line \( f \) is 7 mm. Here \( e \) represents the air gap between the ground plane and the graphene layer that is 0.8 mm which is beneath the substrate. In figure 1, the right side represents stack layer of the antenna with a cross made of copper material with the same length, width and height.

Figure 2 represents a circular patch antenna and figure 3 shows the stack layer structure placed above a circular patch antenna. The antenna consists of a circular copper patch, FR4 substrate and copper ground layer as represented in figure 2. Microstrip line feed is made up of copper material. The antenna is superstrated with stack layer consisting of FR4 superstrate as represented in figure 3. The radius of the circular patch is 18 mm. Width and length of the FR4 substrate are 40 mm as shown in figures 2 and 3. The height of the substrate is 1.6 mm. The ground plane is having 40 mm length and width with 1 mm thickness. The dimension of the feed line is set as 7 mm length, 2 mm width and 0.5 mm height. Table 1 show different dimension values of the microstrip patch antenna. Substrate area is \( 40 \times 40 \) mm\(^2\). The copper stack area is \( 18 \times 8 \) mm\(^2\). Copper patch thickness is taken 0.5 mm with its radius 18 mm. Feed line is placed at 7 mm. Ground plane and substrate thickness is 0.8 mm.

Top view of the microstrip patch antenna is presented in figure 3. The shorting pins are represented by black dots. The distance from the centre of the antenna to the shorting pins is denoted by \( d_2 \) which is equal to 8 mm. The shorting pins are used to connect ground plane and patch. Figure 4 represents the honeycomb lattice structure of graphene material layer sheet. The circular shape is subtracted from this sheet to create metamaterial behaviour. The radius of the circular shape \( R_1 \) is 3 mm. The distance between the centres of the two circles is denoted by \( R_2 \) having

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**Figure 7.** Voltage standing wave ratio versus frequency plot of a microstrip antenna at different graphene chemical potential \( \mu_c \). VSWR shift (tuning) at different frequency range is achieved by changing the chemical potential \( \mu_c \) of graphene from 0 eV to 0.09 eV. (Blue line represent 0 eV, Red line represent 0.03 eV, green line represent 0.06 eV and black line represent 0.09 eV). The frequency range is 1 GHz to 4 GHz.

**Figure 8.** Reflectance plot at different graphene chemical potential \( \mu_c \) for 1 GHz to 4 GHz frequency range. Colour bar indicates normalized reflectance where blue colour corresponds to minimum reflectance and red colour indicates maximum reflectance.
Figure 9. Gain of the antenna with the plus shaped stack. (a) 2D radiation pattern and (b) 3D polar plot with applied μc of 0 eV at frequency 1.98 GHz with achieved gain of 2.91 dB. (c) 2D radiation pattern and (d) 3D polar plot with applied μc of 0 eV at frequency 2.76 GHz with achieved gain of 7.55 dB. (e) 2D radiation pattern and (f) 3D polar plot with applied μc of 0 eV at frequency 3.29 GHz with achieved gain of 2.8 dB.

10 mm. (grey colour represent the graphene layer). Figure 5 is showing the different voltage pads provided to the graphene sheet to give equal chemical potential to the graphene layer.

2.1. Graphene conductivity model
The surface conductivity of graphene has been considered as the Kubo formula [22].

\[
\sigma(\omega, \mu_c, \Gamma, T) = \frac{ie^2}{\pi \hbar^2} \left[ \frac{1}{(\omega - j2\Gamma)^2} \int_{\infty}^{0} \left( \frac{\partial f_0(\varepsilon)}{\partial \varepsilon} - \frac{\partial f_0(-\varepsilon)}{\partial \varepsilon} \right) d\varepsilon \right. \\
\left. - \int_{\infty}^{0} \frac{f_0(-\varepsilon) - f_0(\varepsilon)}{(\omega - j2\Gamma)^2 - 4(\varepsilon/\hbar)^2} d\varepsilon \right],
\]

(1)
Where, the first term is due to intraband contributions, and the second term due to interband contributions, electron charge is represented as $e$, $\omega$ is radian frequency, $\mu_c$ is chemical potential, $\Gamma$ is a phenomenological scattering rate that is assumed to be independent of energy $\varepsilon$, $T$ is temperature and $\hbar$ is the reduced Planck’s constant. In equation (1), $f_B(\varepsilon) = \left( e^{\varepsilon - \mu_c/k_B T} + 1 \right)^{-1}$ is the Fermi–Dirac distribution where $k_B$ is Boltzmann’s constant [23].

Figure 10. Gain of the antenna without a plus-shaped stack superstrate layer. (a) 2D radiation pattern and (b) 3D polar plot with applied $\mu_c$ of 0 eV at 1.98 GHz with maximum gain of −6.95 dB and (c) 2D radiation pattern and (d) 3D polar plot at 2.76 GHz with applied $\mu_c$ of 0 eV with maximum gain of 3.77 dB and (e) 2D radiation pattern and (f) 3D polar plot with applied $\mu_c$ of 0 eV at 3.29 GHz with $\mu_c$ 0 eV with maximum gain of −1.63 dB.
The reflectance mainly depends on the graphene chemical potential and frequency. The wave-vector component when the wave is incident with angle $\theta_i$ is given by $k = \omega \sin \theta_i / c$. The reflection coefficient is given by [24]:

$$r(\omega, \theta_i) = \frac{\omega \cos \theta_i \prod_{00} (\omega, \theta_i)}{2\hbar c k^2 + \omega \cos \theta_i \prod_{00} (\omega, \theta_i)}$$  \hspace{1cm} (2)

Here, $\prod_{\mu \nu} (\omega, \theta)$ - graphene polarization tensor, $\mu, \nu = 0, 1, 2$ and $\prod = \prod_{\mu} \mu$.

Figure 11. (a) 2D radiation pattern and (b) 3D polar plot with applied $\mu_c$ of 0.03 eV at frequency 2.14 GHz with achieved gain of 5.12 dB. (c) 2D radiation pattern and (d) 3D polar plot with applied $\mu_c$ of 0.03 eV at frequency 2.81 GHz with achieved gain of 6.28 dB. (e) 2D radiation pattern and (f) 3D polar plot with applied $\mu_c$ of 0.03 eV at frequency 3.38 GHz with achieved gain of 2.41 dB.
Optical conductivity of graphene material is denoted by $\sigma$ and given by the following equation:

$$\sigma_{||}(\omega, k) = -i\frac{\omega}{4\pi\hbar k^2} \prod_{00} (\omega, k)$$  \hspace{1cm} (3)

from all the above equations, the relationship between the conductivity and reflectance is given by:

$$r(\omega, \theta) = \frac{2\pi \cos \theta \sigma_{||}(\omega, k)}{\varepsilon + 2\pi \cos \theta \sigma_{||}(\omega, k)}$$ \hspace{1cm} (4)

$$\mathcal{R}(\omega, \theta) = |r(\omega, \theta)|^2$$ \hspace{1cm} (5)

The relationship between the conductivity and reflectance is changed if the complex part is considered and is given by:

Figure 12. (a) 2D radiation pattern and (b) 3D polar plot with applied $\mu_c$ of 0.06 eV at frequency 2.32 GHz with achieved gain of 6.31 dB. (c) 2D radiation pattern and (d) 3D polar plot with applied $\mu_c$ of 0.06 eV at frequency 3.05 GHz with achieved gain of 7.63 dB. (e) 2D radiation pattern and (f) 3D polar plot with applied $\mu_c$ of 0.06 eV at frequency 3.46 GHz with achieved gain of 2.11 dB.
Now if $\theta_i = k=0$, The reflectance for the incident wave is given by:

$$
\mathcal{R}(\omega, \theta_i) = \mathcal{R}(\omega, 0) = \frac{4\pi^2 \sigma(\omega)}{[c + 2\pi Re\sigma(\omega)]^2 + 4\pi^2 Im^2 \sigma(\omega)}
$$

From the equations (2)–(7), it is clear that the graphene chemical potential and its conductivity closely related to reflectance [24].
3. Results and discussions

The design presented in section 2 is analyzed using COMSOL Multiphysics RF module and results achieved through this simulation is presented in figures 5–14.

The reflection coefficient is tuned by changing the graphene chemical potential in figure 5. When chemical potential ($\mu_c$) 0 eV is applied, then three bands of reflection coefficient are obtained. From these three bands, the first band is obtained at 1.98 GHz of resonant frequency with reflection coefficient of $-12.18$ dB and bandwidth of 10 MHz is achieved, the second band is obtained at 2.76 GHz of resonant frequency with reflection coefficient of $-26.48$ dB and bandwidth of 150 MHz is achieved and the third band is obtained at 3.29 GHz of resonant frequency with reflection coefficient of $-21.35$ dB and bandwidth of 160 MHz is obtained. When chemical potential ($\mu_c$) of 0.03 eV is applied, the resonance frequency (reflection coefficient) shift with the reference of 0 eV, is clearly visible in figure 5. When chemical potential ($\mu_c$) of 0.03 eV is applied, then the maximum three bands of reflection coefficient are obtained. From these three bands, the first band is obtained at 2.14 GHz of resonant frequency with a reflection coefficient of $-22.76$ dB and bandwidth of 30 MHz, the second band is obtained at 2.81 GHz of resonant frequency with reflection coefficient of $-30.39$ dB and the bandwidth of 130 MHz and third band obtained at 3.05 GHz of resonant frequency with bandwidth of 210 MHz. When chemical potential ($\mu_c$) of 0.06 eV is applied, the resonance frequency (reflection coefficient) shift with the reference of 0.03 eV, is clearly shown in figure 5. When chemical potential ($\mu_c$) of 0.06 eV is applied, then a maximum of three bands of the reflection coefficient is obtained. From these three bands, the first band is obtained at 3.32 GHz of resonant frequency with a reflection coefficient of $-26.1$ dB and bandwidth of 70 MHz is achieved. The second band is obtained at 3.05 GHz of resonant frequency with a reflection coefficient of $-23.61$ dB and the bandwidth of 90 MHz. The third band is obtained at 3.46 GHz of resonant frequency with a reflection coefficient of $-21.01$ dB and bandwidth of 240 MHz. When chemical potential ($\mu_c$) of 0.09 eV is applied, the resonance frequency (reflection coefficient) shift with the reference of 0.03 eV, is clearly presented in figure 5.

When chemical potential ($\mu_c$) of 0.09 eV is applied, then the maximum three bands of reflection coefficient are obtained. From these three bands, the first band is obtained at 2.4 GHz of resonant frequency with a reflection coefficient of $-27.36$ dB and bandwidth of 80 MHz, the second band is obtained at 3.05 GHz of

![Figure 14](image-url)

Figure 14. [a] Electric field with $\mu_c$ 0 eV at Frequency 2.76 GHz. [b] Electric field with $\mu_c$ 0.03 eV at frequency 2.81 GHz. [c] Electric field with $\mu_c$ 0.06 eV at frequency 2.32 GHz. [d] Electric field with $\mu_c$ 0.09 eV at frequency 2.4 GHz.
resonant frequency with a reflection coefficient of $-25.12$ dB and the bandwidth of 60 MHz. The third band is obtained at 3.46 GHz of resonant frequency with a reflection coefficient of $-20.43$ dB and bandwidth of 220 MHz. The comparison of graphene chemical potential, frequency and bandwidth for graphene sheet with circular slots is presented in table 2 and graphene sheet without circular slot design.

Figure 6 shows the Voltage Standing Wave Ratio (VSWR) of the microstrip antenna at different graphene chemical potential. Figure 7 represents reflectance at a different chemical potential ($\mu_c$) (0.01 eV, 0.03 eV, 0.06 eV and 0.09 eV) for 1 GHz to 4 GHz frequency range. In this, the colour bar indicates normalized reflectance where a blue colour corresponds to minimum reflectance and red colour indicates maximum reflectance. From this figure, it is observed that with applied different chemical potential, the resonant frequency is tuned.

Table 2. Bandwidth of antenna with a circular slot in the graphene sheet.

| No. | $\mu_c$ (eV) | Resonant Frequency (GHz) | Bandwidth (MHz) |
|-----|-------------|------------------------|-----------------|
| 1   | 1.98        | 2.76                   | 150             |
| 2   | 0           | 3.29                   | 160             |
| 3   | 2.14        | 2.81                   | 130             |
| 4   | 0.03        | 3.38                   | 210             |
| 5   | 0.06        | 3.64                   | 100             |
| 6   | 0.09        | 3.87                   | 70              |
| 7   | 0.09        | 3.87                   | 70              |
| 8   | 0.09        | 3.87                   | 70              |
| 9   | 0.09        | 3.87                   | 70              |

Table 3. Bandwidth of antenna without a circular slot in the graphene sheet.

| No. | $\mu_c$ (eV) | Resonant Frequency (GHz) | Bandwidth (MHz) |
|-----|-------------|------------------------|-----------------|
| 1   | 2.84        | 3.57                   | 130             |
| 2   | 0           | 3.67                   | 80              |
| 3   | 0.06        | 3.34                   | 100             |
| 4   | 0.09        | 3.64                   | 100             |
| 5   | 0.06        | 3.87                   | 70              |
| 6   | 0.09        | 3.87                   | 70              |
| 7   | 0.09        | 3.87                   | 70              |
| 8   | 0.09        | 3.87                   | 70              |

Table 4. Gain of the antenna with and without plus shaped superstrate layer.

| No. | Results of antenna | $\mu_c$ (eV) | Resonant Frequency (GHz) | Gain (dB) |
|-----|---------------------|-------------|------------------------|-----------|
| 1   | With plus           | 1.98        | 2.91                   | 2.91      |
| 2   | Shaped stack layer  | 0           | 2.76                   | 7.55      |
| 3   | Without plus       | 3.29        | 2.8                    | -6.95     |
| 4   | Shaped stack layer  | 0           | 2.76                   | 3.77      |
| 5   | Shaped stack layer  | 3.29        | -1.63                  |           |
Table 5. Comparison table of Reflection Coefficient, Bandwidth, VSWR, Gain and tuning of spectrum results at different graphene chemical potential.

| No. | \( \mu_c \) (eV) | Resonant Frequency (GHz) | Reflection coefficient (dB) | Gain (dB) | VSWR | Bandwidth (MHz) | Frequency Tuning (MHz with reference \( \mu_c \) (eV)) | Reference |
|-----|------------------|---------------------------|-----------------------------|-----------|-------|----------------|----------------------------------------|-----------|
| 1   | 0.03             | 2.14                      | -22.76                      | 5.12      | 1.1   | 130           | 0 (eV)                                | 90        |
| 2   | 0.06             | 3.05                      | -23.61                      | 7.63      | 1.1   | 90            | 240 (MHz)                              | 0.03 (eV) |
| 3   | 0.09             | 3.25                      | -25.12                      | 9.42      | 1.1   | 60            | 200 (MHz)                              | 0.06 (eV) |

Figures 9–10 represents the design results in terms of 2D radiation pattern and 3D polar plot for microstrip antenna without a plus-shaped superstrate layer. The maximum gain of 3.77 dB is achieved for graphene chemical potential of 0 eV at 2.76 GHz. The comparative results of gain for both designs (with and without plus shaped superstrate layer) are presented in table 4. From the table, it is clear that the addition of the superstrate layer increases the gain of the antenna. The maximum gain of 7.55 dB is achieved for the microstrip patch antenna design with a plus-shaped stacked superstrate layer.

2D radiation pattern (figure 11(A)) and 3D polar plot (figure 11(B)) with applied \( \mu_c \) of 0.03 eV at frequency 2.14 GHz with achieved gain of 5.12 dB. 2D radiation pattern (figure 11(C)) and 3D polar plot (figure 11(D)) with applied \( \mu_c \) of 0.03 eV at frequency 2.81 GHz with achieved gain of 6.28 dB. 2D radiation pattern (figure 10(E)) and 3D polar plot (figure 11(F)) with applied \( \mu_c \) of 0.03 eV at frequency 3.38 GHz with achieved gain of 2.41 dB.

Figure 12 show the radiation pattern and polar plot for 0.06 eV graphene chemical potential. The highest gain of 7.63 dB is achieved for 3.05 GHz. Figure 13 show the radiation pattern and polar plot for 0.09 eV graphene chemical potential. The highest gain of 9.42 dB is achieved for 2.25 GHz frequency. Electric field response to different chemical potential is presented in figure 14. Table 2 shows the results in terms of the reflection coefficient, gain, bandwidth for different graphene chemical potential. The tuning of the frequency with respect to different chemical potential is also presented in the table. The maximum reflection coefficient, gain, bandwidth of \(-30.39 \text{ dB}, 9.42 \text{ dB}, 240 \text{ MHz}\) are achieved respectively. The maximum tuning of \(240 \text{ MHz}\) is achieved by changing the graphene chemical potential from 0 eV to 0.03 eV.

The comparative results in terms of reflection coefficient, graphene chemical potential, gain, bandwidth are presented in table 5. The comparison clearly shows that maximum gain of 9.42 dB and a maximum bandwidth of 240 MHz is achieved.

4. Conclusion

The graphene-based microstrip antenna is presented to improve the gain and tune the frequency spectrum. The analysis in terms of the reflection coefficient, bandwidth, radiation pattern, and the gain polar plot is obtained. Multiband and tunable frequency response are observed and tuning is achieved by changing the graphene chemical potential. Designed antenna results into highest gain of 9.42 dB at 3.25 GHz and \( \mu_c = 0.09 \text{ eV} \) with \(-25.12 \text{ dB} \) reflection coefficient value. The tunability of frequency is observed with different chemical potential of graphene. The maximum tuning of 240 MHz is achieved by changing the graphene chemical potential from 0 eV to 0.03 eV. It is also observed that the bandwidth of the proposed antenna increases with an increase in the chemical potential. The maximum bandwidth of 240 MHz is achieved with 0.06 eV graphene chemical potential at 3.46 GHz frequency. The proposed reconfigurable antenna can be a potential candidate for various RF and microwave application in L and S bands.
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ORCID IDs

Vigneswaran Dhasarathan https://orcid.org/0000-0003-3375-4821
Mayurkumar Ladumor https://orcid.org/0000-0001-6491-9807
Shobhit K. Patel https://orcid.org/0000-0002-0117-2440

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