

RESEARCH ARTICLE

Reconfigurable wearable antenna for 5G applications using nematic liquid crystals

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Abstract

The antenna is one of the key building blocks of many wearable electronic devices, and its functions include wireless communications, energy harvesting, and radiative wireless power transfer. In an effort to realize lightweight, autonomous, and battery-less wearable devices, we demonstrate a reconfigurable antenna design for 5G wearable applications that requires ultra-low driving voltages (0.4–0.6 V) and operates over a high frequency range (3.3–3.8 GHz). For smart glasses applications, previous antenna designs were ‘fixed’ and mounted on the eyeglass frame itself. Here, we demonstrate a reconfigurable design that could be achieved on the lens itself using an anisotropic liquid crystal (LC) material. We demonstrate how liquid crystal alignment and electric field patterns strongly influence the tuning capabilities of these antennas in the gigahertz range and present a smart, reconfigurable spiral antenna system with a liquid crystal substrate.

KEYWORDS

liquid crystals, smart glasses, tunable antenna

1 | INTRODUCTION

The electronic antenna is a circuit element that transforms a guided wave in transmission lines into a free-space wave and vice versa. Antennas are essential components for wireless communication systems and are widely used in both wearable and implantable devices. The two main applications of antennas in the literature are energy harvesting^[1] and data transmission.^[2] In this article, we demonstrate how an antenna’s frequency can be tuned using liquid crystal (LC) materials, making it appealing for a range of energy harvesting and telecommunications applications.

Multi-functional wearable devices require both a wide frequency bandwidth and a miniaturized scale. For energy harvesting applications, a tunable frequency bandwidth device enables multiple radio frequency (RF) wavelengths in free space to be harvested. Similarly, for communications applications, a tunable antenna enables wearable devices to transmit and receive broadband information^[3] and helps reduce mismatch and noisy interference when communicating with other devices.^[4] In addition, and in comparison with traditional antennas, a tunable antenna can establish communication with multiple devices with different frequencies, which could play an important role in Multiple In Multiple Out (MIMO) networks,^[5]

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making dynamically tunable antenna front ends a necessity in the near future. Consequently, we demonstrate a tunable antenna design that covers the frequency range of communications systems and consumes minimum energy in a limited area. Such an antenna design could be mounted on wearable or implantable devices to enable both communications and energy harvesting capabilities.

There are many tunable antenna strategies reported in the literature. For example, the method demonstrated by Huang et al. involved tuning the impedance of the matching network to change the reflection coefficient of frequency.^[6] Other previous studies attempted to achieve electronic reconfigurability of the reflective arrays using varactor diodes.^[7] Other methods involved using reconfigurable substrate materials, such as controllable dielectrics^[8,9] and barium strontium titanate.^[10] However, the complexity of these approaches are not optimal when targeting wearable devices. In terms of LC-tunable antennas, Gaebler et al. devised a novel tunable antenna for millimeter wave applications^[11] using a commercial nematic liquid crystal (NLC) mixture, K15. According to their results, the resonant frequency could be tuned from 33.25 to 37.1 GHz, with a driving voltage reaching 20 V to tune the LC substrate. Obviously, this driving voltage is impractical for a wearable application, and the purpose of our article is to demonstrate that such a tunable wavelength range can be achieved using a much smaller driving voltage, making use of the previously-demonstrated results showing that LCs demonstrate excellent RF performance in the gigahertz range and that the frequency range and tunable bandwidth can be expanded using different LC mixture materials.^[12,13]

As utilized in the above-mentioned papers, and in the present work, the key benefit of LC-based antennas is their ability to exhibit analogue tuning of properties such as their permittivity and refractive index. This ability stems from the anisotropic nature of the LC phase which, at the molecular level, consists of anisotropic molecules which may be, for instance, rod-shaped or disc-shaped. This molecular shape anisotropy results in orientational, and sometimes positional order, which then translates into a bulk phase anisotropy. This orientational ordering of the molecules means that the 'director', the ensemble average direction of LC molecular orientation, can be defined.^[14] These anisotropic properties allow LCs to be manipulated through a balance of forces and torques due to an applied electric field and elastic effects, yielding a reconfigurable design where the bandwidth of the antenna can be easily and accurately tuned.^[15,16] In the present work we will consider those LCs that exhibit orientational anisotropy but no positional anisotropy, termed 'nematic' liquid crystals (NLCs).

Examples of antennas mounted on smart glasses are shown in Figure 1A(i) and (ii).^[17,18] In Figure 1A(i), the antenna was placed on the eye-glass frame. In addition to such an antenna being fixed, placement on the eye-glass frame results in a bulky design frame. In Figure 1A(ii), the antenna is instead placed at the far edge of the lens, which can reduce the size of the glasses frame without directly blocking the user's view. Here, we propose a tunable antenna that is integrated into 'intelligent' glasses, where the antenna and the LC substrate are mounted on the glass lens, as shown in Figure 1A(iii). According to the literature, antennas mounted on the far edge of the lens can minimize the influence of vision obstruction.^[18] Moreover, our proposed design consists of transparent materials to avoid blocking the user's view. Overall, the proposed antenna consists of a dielectric layer, an electrode layer and an LC layer, as shown in Figure 1B. As previously mentioned, the LC director orientation is influenced by an applied electric field. Therefore, our hypothesis involves 'tuning' the antenna's bandwidth by switching our LC directors from an initial planar state to a state determined by an applied voltage, which leads to a variation of the material's dielectric permittivity.^[19]

The key design parameters for this technology are therefore to fit the dimensions of typical eye glass lenses, have high transparency, operate at a low voltage and with a target frequency. With regard to transparency, previous transparent antenna designs have achieved average antenna transmittance of around 81%, sufficiently high as to avoid impacting a user's vision,^[18] and in our design, we therefore aim for transparency higher than 80%. Moreover, since high voltages are unacceptable for wearable devices, and where the power supply of smart electronics is usually around 3 to 5 V^[20] we aim for voltages lower than 5 V. As is mentioned in previous papers, the 5G network will be used in the future development of most 'Internet of Things' (IoT) applications,^[21] so we aim to design and tune the antenna within a 5G frequency band.

In the present paper we demonstrate a 'proof-of-principle' of using LCs for the design of an antenna with the above design requirements. We use LC and antenna simulations to demonstrate the feasibility of such a device. Our results illustrate that the proposed tunable antenna could be driven with 0.4 to 0.6 V and cover the section of the 5G communication frequency range from 3.3 to 3.8 GHz, which both more than adequately satisfy the design criteria for wearable applications. Apart from telecommunication applications, the tunable antenna could also be used to harvest energy from within the 5G frequency range. In comparison with previous designs, our design has a smaller footprint, thinner substrate material and lower driving voltages, which is more suitable for wearable applications.

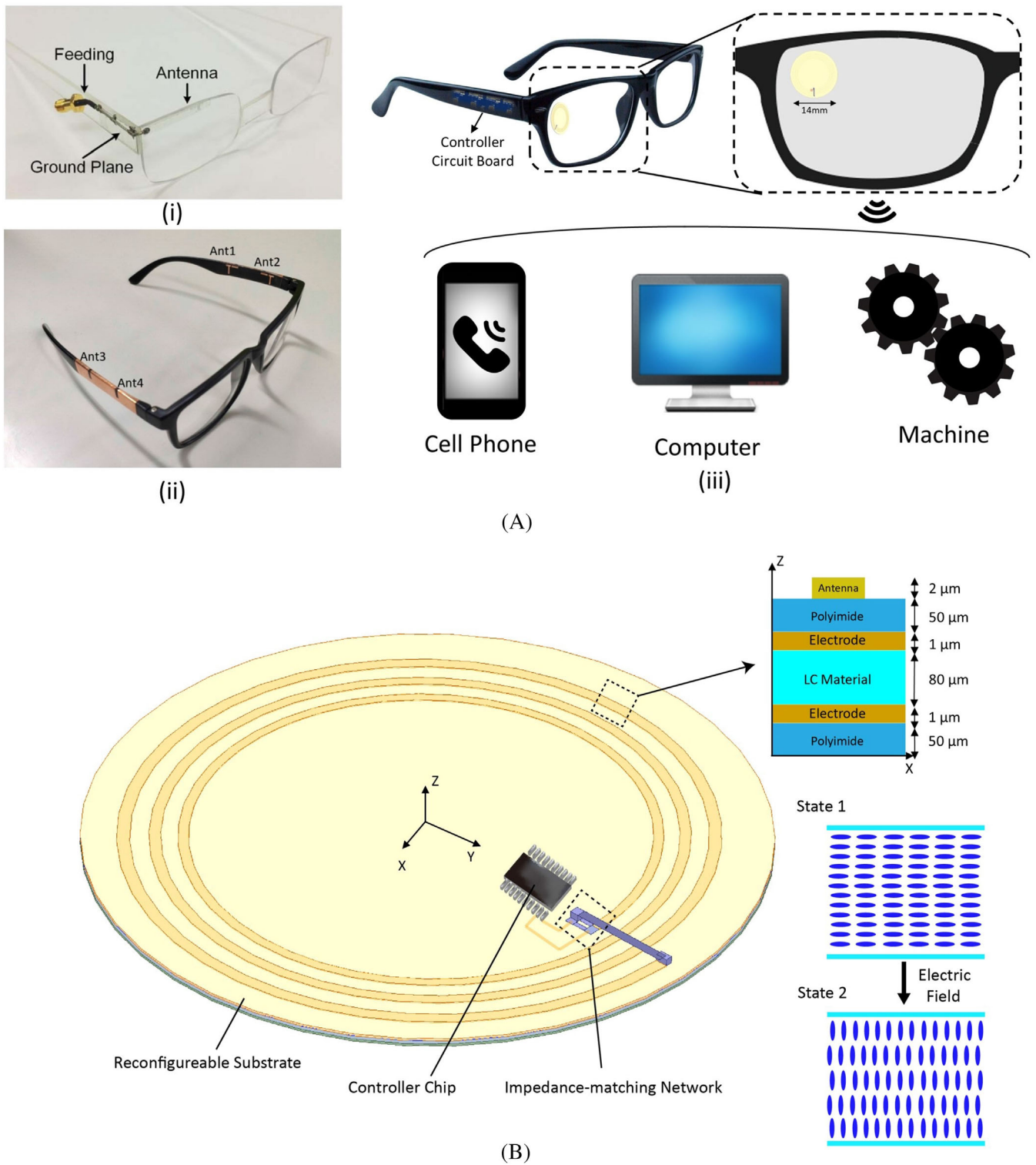


FIGURE 1 A, (i) and (ii) show previous antenna designs for smart glasses, where in (i) a transparent antenna is mounted on the lens (used with permission from^[18]) and in (ii) a patch antenna is mounted on the frame of the glasses (used with permission from^[17]) A, (iii) shows how the proposed antenna could fit on the lens of a smart glass in our design, as well as possible applications of this tunable antenna. B, Schematic diagram of the tunable antenna and the structure of the reconfigurable layer.

2 | METHODOLOGY

2.1 | Theoretical framework

As previously mentioned, the orientation of the NLC director can be altered through a balance of effects due to an applied electric (or magnetic) field and internal elasticity. The director configuration that minimizes the total free energy, which comprises of electrostatic and elastic components, will be the one observed, and can be tuned by varying the applied voltage. These two effects are mathematically formulated through the electrostatic energy density F_{es} , which depends on the anisotropic dielectric properties of the material described in terms of a rank-2 dielectric permittivity tensor $\boldsymbol{\varepsilon}$, and the bulk nematic energy density which consists of an elastic component F_{el} and a thermotropic component F_{th} . Once the director profile that minimizes the free energy is determined, the optical phase profile of the LC material may then be calculated.

Although the free energy density components may be written in terms of the director, $\mathbf{n}(\mathbf{x})$, problems occur in such a models when high gradients of $\mathbf{n}(\mathbf{x})$ are present, for instance near electrode edges. We therefore use the Landau de Gennes (LdG) model of a nematic LC (NLC), whereby the alignment of the molecules in the LC state is described in terms of both a degree of orientational order, $S(\mathbf{x})$, and the preferred direction of orientation, $\mathbf{n}(\mathbf{x})$. Each free energy component is then written in terms of the 'Q-tensor', a rank-2 tensor, which takes the form:

$$\mathbf{Q} = S \left(\mathbf{n} \otimes \mathbf{n} - \frac{\mathbf{I}}{3} \right), \quad (1)$$

where \mathbf{I} is the identity matrix. The total free energy (\mathcal{F}) of the NLC can be written as the volume integral of the sum of the elastic (F_{el}), thermotropic (F_{th}) and electrostatic energy (F_{es}) density functions:

$$\mathcal{F} = \int_V (F_{el} + F_{th} + F_{es}) dV. \quad (2)$$

The application of an electric field to an NLC induces dipoles, which may be caused by induced molecular dipoles and/or reorientation of enhanced existing molecular dipoles, which causes the director to align either parallel or perpendicular to the electric field, depending on the largest dielectric permittivity of the material. The preference for parallel or perpendicular alignment with an applied electric field is therefore determined by the dielectric anisotropy, $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp}$, the difference in permittivities parallel and perpendicular to the molecu-

lar axis.^[22] The dielectric displacement field due to these dielectric effects is then:

$$\mathbf{D} = \varepsilon_0 \boldsymbol{\varepsilon} \mathbf{E}, \quad (3)$$

where ε_0 is the permittivity of free space and $\boldsymbol{\varepsilon}$ is the dielectric permittivity tensor, which can be expressed in terms of the Q-tensor as^[23]:

$$\boldsymbol{\varepsilon} = \frac{\Delta\varepsilon}{S_{eq}} \mathbf{Q} + \tilde{\varepsilon} \mathbf{I}, \quad (4)$$

and where, $\tilde{\varepsilon} = (2\varepsilon_{\perp} + \varepsilon_{\parallel})/3$ is the average permittivity and S_{eq} is the order parameter in the bulk of the LC at which the experimental measurement of $\Delta\varepsilon$ was undertaken. The resulting electrostatic energy density of the NLC is:

$$F_{es} = -\frac{1}{2} \mathbf{D} \cdot \mathbf{E} = -\frac{1}{2} \varepsilon_0 (\boldsymbol{\varepsilon} \mathbf{E}) \cdot \mathbf{E} = -\frac{1}{2} \varepsilon_0 \boldsymbol{\varepsilon} \nabla U \cdot \nabla U, \quad (5)$$

where U is the electric potential and $\mathbf{E} = -\nabla U$.

Using the commonly assumed one-constant approximation for the elastic constants of the NLC,^[14] the elastic energy density and thermotropic energy density may be written as:

$$F_{el} = \frac{L}{2} |\nabla \mathbf{Q}|^2 \text{ and } F_{th} = A \text{tr}(\mathbf{Q}^2) + \frac{2B}{3} \text{tr}(\mathbf{Q}^3) + \frac{C}{2} \text{tr}(\mathbf{Q}^4), \quad (6)$$

where L is an average elastic constant related to the splay bend and twist constants K_{11} , K_{22} , and K_{33} , $\text{tr}(\cdot)$ signifies the trace of a tensor, $A = a(T - T^*) = a\Delta T$ is a temperature dependent coefficient, with $a > 0$ and T^* the temperature at which the isotropic state $\mathbf{Q} = 0$ becomes unstable, and B and C are assumed to be temperature independent. In the simulations below, these coefficients were set to $A = -6.5 \times 10^5 \text{ Nm}^{-2}$, $B = -16 \times 10^5 \text{ Nm}^{-2}$ and $C = 39 \times 10^5 \text{ Nm}^{-2}$.^[14]

The total free energy density is therefore written as:

$$\mathcal{F} = \int_V \left[\frac{L}{2} |\nabla \mathbf{Q}|^2 + A \text{tr}(\mathbf{Q}^2) + \frac{2B}{3} \text{tr}(\mathbf{Q}^3) + \frac{C}{2} \text{tr}(\mathbf{Q}^4) - \frac{1}{2} \varepsilon_0 \boldsymbol{\varepsilon} \nabla U \cdot \nabla U \right] dV. \quad (7)$$

The equilibrium director configuration can be obtained by minimizing the total free energy in Equation (7) using the calculus of variations, which leads to the partial differential equations for the minimizing Q-tensor components,

$$\left(\frac{\partial F_b}{\partial Q_{i,j}} \right)_{,j} = \frac{\partial F_b}{\partial Q_i}, \quad (8)$$

where the \cdot_j subscript denotes partial differentiation with respect to the j^{th} component of the position vector, which in our present two-dimensional setting is $\mathbf{x} = (x, z)$, and the summation convention has been used. Together with the equation for the components of the \mathbf{Q} -tensor, Gauss's law for the electric potential must be simultaneously solved,

$$0 = \nabla \cdot \mathbf{D} = \nabla \cdot (\epsilon_0 \epsilon \mathbf{E}) = -\epsilon_0 \nabla \cdot ((\epsilon \nabla U)) = -\epsilon_0 (\epsilon_{ij} U_{,j})_{,i}. \quad (9)$$

In our previous work, a 2×2 Jones matrix method was used to calculate the optical properties for a specific direction profile $\mathbf{n}(\mathbf{x})$,^[24] where the optical properties of the cell is calculated using a multi-layer method, dividing the LC cell into thin layers, assuming the director to be constant in each layer, and thus determining the transmittance through each layer. This method is suitable for thin cells since the reflections between the layers are neglected. However, in the current tunable antenna design, a relatively thick LC cell (80 μm) is used, and the Berreman 4×4 matrix method, a more accurate optical model, is introduced here to calculate the transmittance. This optical calculation includes consideration of multiple reflections of the electric and magnetic waves between layers. The dielectric permittivity is then a function related to the axis z perpendicular to the layers and the Berreman matrix, which encodes the optical electric and magnetic fields within each layer, can be written as:

$$D = \begin{bmatrix} -\eta \frac{\epsilon_{31}}{\epsilon_{33}} & 1 - \frac{\eta^2}{\epsilon_{33}} & -\eta \frac{\epsilon_{32}}{\epsilon_{33}} & 0 \\ \epsilon_{11} - \frac{\epsilon_{13}\epsilon_{31}}{\epsilon_{33}} & -\eta \frac{\epsilon_{13}}{\epsilon_{33}} & \epsilon_{12} - \frac{\epsilon_{13}\epsilon_{32}}{\epsilon_{33}} & 0 \\ 0 & 0 & 0 & 1 \\ \epsilon_{21} - \frac{\epsilon_{23}\epsilon_{31}}{\epsilon_{33}} & -\eta \frac{\epsilon_{23}}{\epsilon_{33}} & \epsilon_{22} - \frac{\epsilon_{23}\epsilon_{32}}{\epsilon_{33}} - \eta^2 & 0 \end{bmatrix}, \quad (10)$$

where η is the component of the incident light in the x -direction.

Due to the symmetry of the permittivity tensor, $D_{13} = D_{24}$, $D_{11} = D_{22}$ and $D_{41} = D_{23}$, which allows the Maxwell equations to be simplified and the output light vector to be determined.^[25] This modeling method was used to calculate the transmittance of the LC cell.

2.2 | Design

To realize the controllable antenna, we proposed a multi-layer substrate with a sandwich structure consisting of

TABLE 1 Material parameters for the LCs considered during this study.^[27–33] The parameters for RDP-84909 are provided by DIC corporation, Japan.

Parameter	5CB	BLO48	RDP-84909	E7
Clearing temperature, T^{NI} ($^{\circ}\text{C}$)	35	100	91.7	59.85
ϵ_{\perp}	6.9	5.2	8	5.17
$\Delta\epsilon$	11	16.9	39.1	14.37
n_o ($\lambda = 532\text{nm}$)	1.532	1.573	1.48	1.53
Δn ($\lambda = 532\text{nm}$)	0.174	0.226	0.1464	0.22
K_{11} (pN)	6.4	15.5	4.6	11.2
K_{22} (pN)	3	12	1.2	6.8
K_{33} (pN)	10	28	13.8	17.8

dielectric layers, grid electrodes, LC material and alignment layers. The dielectric layer, typically polyimide (PI), protects the user's eyes from the electric field. A transparent electrode layer consisting of indium tin oxide (ITO) was used, as well as a planar alignment layer, which can be achieved by rubbing the PI layer in one direction, creating microgrooves along which the LC aligns.^[26] Moreover, the LC cell thickness can be fixed through the use of SiO_2 micro-spheres spacer within the LC layer.

In Table 1, we list four commonly available NLC materials and mixtures. When choosing the NLC material for this application low LC driving voltages are needed to ensure device safety and portability, and therefore LCs with high $\Delta\epsilon$ and low K_{11} are more suitable for low-power applications. Furthermore, relatively low splay, twist, and bend elastic constants (K_{11} , K_{22} , and K_{33}) are required to reduce the device response time. Based on these considerations, RDP-84909 (DIC cooperation) was chosen as the most suitable LC material.

A spiral antenna was chosen since it is a commonly used antenna geometry in wearable applications due to its simplicity, universality and low-cost.^[34,35] Our antenna was designed for 5G applications, where we chose n78 from frequency range 1 (FR1) of the 5G mobile network, that is, 3.3–3.8 GHz.^[36] The electromagnetic waves in this range are defined as centimeter waves. Due to their small wavelength, centimeter waves could be received in narrow beams, which is suitable for data linking, point to point communication and radar applications.

As shown in Figure 1B, a single-armed Archimedean spiral coil was chosen for its typical wide bandwidth and circular polarization, and impedance matching was used due to the geometry limitation. In comparison with a traditional patch antenna, the single-armed Archimedean spiral coil design has less antenna area, which can reduce vision obstruction. A matching parallel capacitor was used to adjust the antenna to the desired resonant frequency

with maximized power delivery, using equation^[37]:

$$f = \frac{1}{2\pi\sqrt{L_s C_p}}$$

where L_s is the equivalent inductance of the spiral antenna and C_p represents the total capacitance of the device. Finite element analysis was carried out with High Frequency Structure Simulator (HFSS) software, where the Archimedean spiral geometry was defined as: $r = r_\theta + \alpha\phi$, where $r_\theta = r_0$ and $r_\theta = r_1$ are the inner and outer radii of the starting circle, α is the growth rate of spiral arm, ϕ denotes the angle or the arc value, and the spiral lines were defined as $x_t = r_\theta e^{\alpha t} \cos t$, and $y_t = r_\theta e^{\alpha t} \sin t$. The specific parameters of antenna were defined as follows: $\alpha = 17.5$ mm, $\phi = 6\pi$, $r_0 = 4.5$ mm, $r_1 = 4.7$ mm, $C = 0.8$ pF. Copper elements define the inductance of the spiral coil and the gaps between generate the equivalent capacitance of the device.

The surface current distribution presented in Figure 2A indicates the current flows on the antenna surface, which is restricted by the spiral geometry. Additionally, the induced electric field indicates a higher concentrated electric field intensity on the intermediate spirals. The Specific Absorption Rate (SAR) simulated was constrained to 0.8538 W kg^{-1} as is shown in Figure 2B, which is within the safety regulation standard (2 W kg^{-1}).^[38] The radiation patterns for two different LC state are demonstrated in Figure 2C. The reflection coefficients (S11) are -15.8 and -20.8 dB when ϵ equals to 8 and 47.1, respectively. Additionally, the radiation pattern is slightly changed with two different dielectric permittivity, which showcase that the propagation direction of antenna is stable as the LC substrate is switched.

Grid electrodes were chosen on both the top and bottom electrode layers rather than plate electrodes since the latter would reflect electromagnetic waves and prevent them from reaching the reconfigurable LC layer. In Figure 3A, a top-bottom grid electrode array with $1\mu\text{m}$ width and $49\mu\text{m}$ gap (2% of grid density) were simulated using the Q-tensor theory described above. The grid electrodes have similar performance (in terms of electric field intensity and direction) to plate electrodes and, consequently, the LC molecules exhibit similar behavior with each type of electrode. The transmittance of the cell was then calculated using the 4×4 Berreman matrix method described above, and is also shown in Figure 3A. The transmittance through out the cell is between 91% and 74%. The lowest transmittance occurs where the electrodes are located and therefore the LC cell with grid electrodes would have higher average transmittance than plane electrodes.

The threshold voltage required to tilt the LC directors from planar towards the vertical can be determined

using^[25]

$$V_c = \pi \sqrt{\frac{K_{11}}{\epsilon_0 \Delta \epsilon}},$$

which shows that the cell thickness does not affect the threshold voltage. Although a thick cell will result in a relatively long response time,^[3] thicker LC cells will have a more significant frequency bandwidth variation from switching the director configuration of the LC substrate. In this case, thicker substrates lead to wider antenna tuning frequencies. Therefore, to ensure both the high tunability and low response time, the thicknesses of the LC and PI layers were set to 80 and $50\mu\text{m}$, respectively.

3 | RESULTS AND DISCUSSIONS

As mentioned previously, to reduce the response time, the antenna was mounted on a $180 \mu\text{m}$ reconfigurable substrate. Assuming a relatively weak anchoring effect, we can assume that all LC directors are planar and homeotropically aligned in state 1 (no applied voltage) and state 2 (with applied voltage), respectively. In this case, the theoretical maximum tunable frequency range can be calculated. For the LC RDP-84909, the permittivities of the two states are 47.1 and 8, respectively, and therefore the maximum frequency shift is from 3.09 to 4.15 GHz (Figure 4A), which is in the centimeter wave range.

In practice, due to the anchoring effect of the PI layer on the LC, the directors in contact the edge of the alignment layers tend to maintain their original orientation. Thus, when a voltage larger than the threshold voltage is applied to the cell, the average permittivity of the cell will be smaller than ϵ_{\parallel} . In future works, the average capacitance between electrodes could be calculated using the simulation software TechWiz. Hence, the relative permittivity could be calculated with various input voltages. However, using the model in this work, in Figure 3B the average permittivity is plotted against voltage, known as the Fredericksz curve, and shows a sharp rise of relative permittivity around 0.35 V, which is in agreement with the theoretical threshold voltage of RDP-84909 calculated as 0.362 V. Moreover, the permittivity increases significantly between 0.35 and 1 V, where the permittivity varies from 8 to 38.4. The relative increment of permittivity decreases after 2 V. According to the Fredericksz curve, we see that for significant changes to the permittivity it is possible to operate the reconfigurable substrate within a relatively small voltage range, between 0.35 and 1 V is preferred, an ideal range for wearable applications.

Simulations were then performed to obtain the relationship between LC substrate permittivity found through the

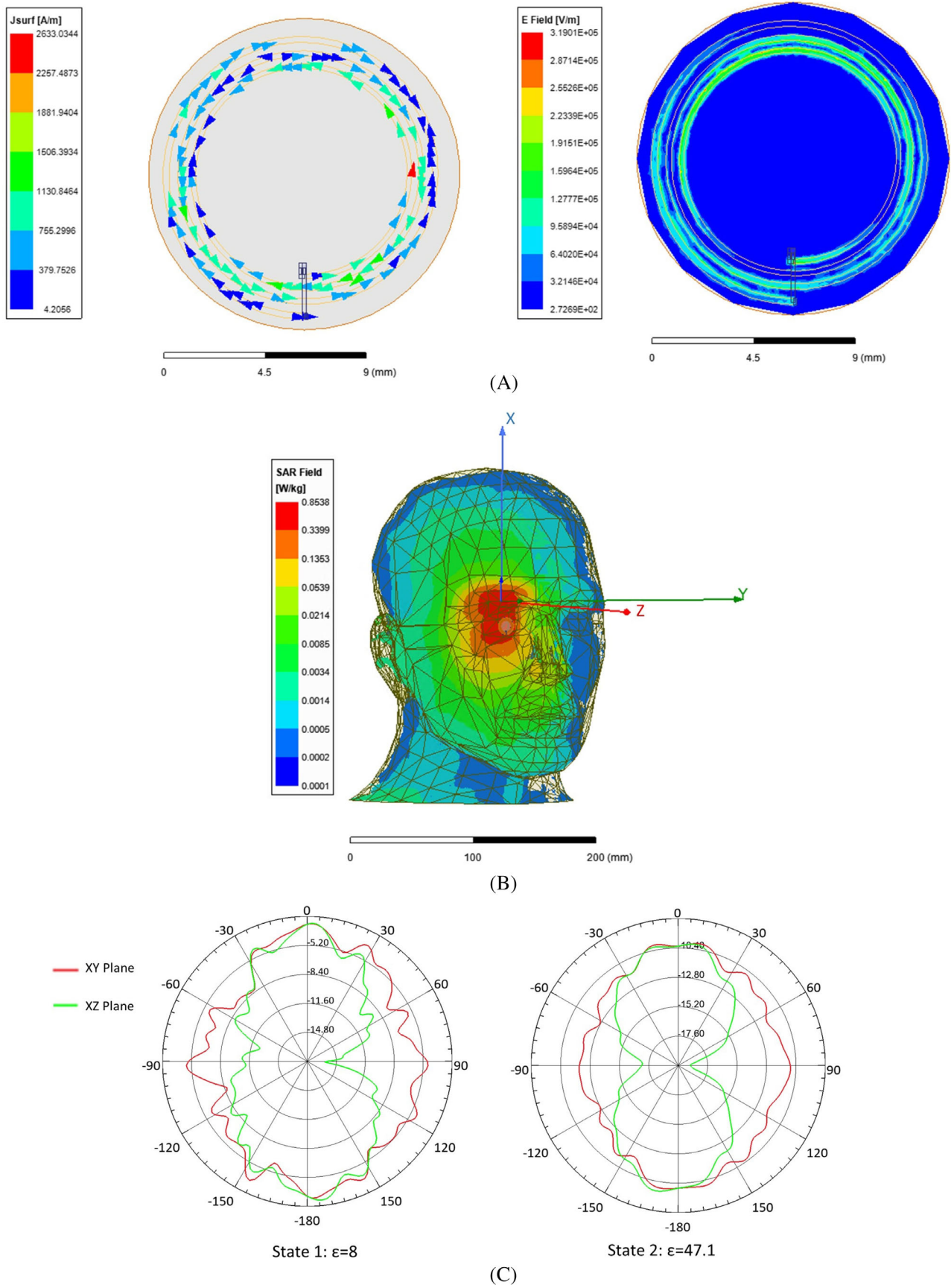
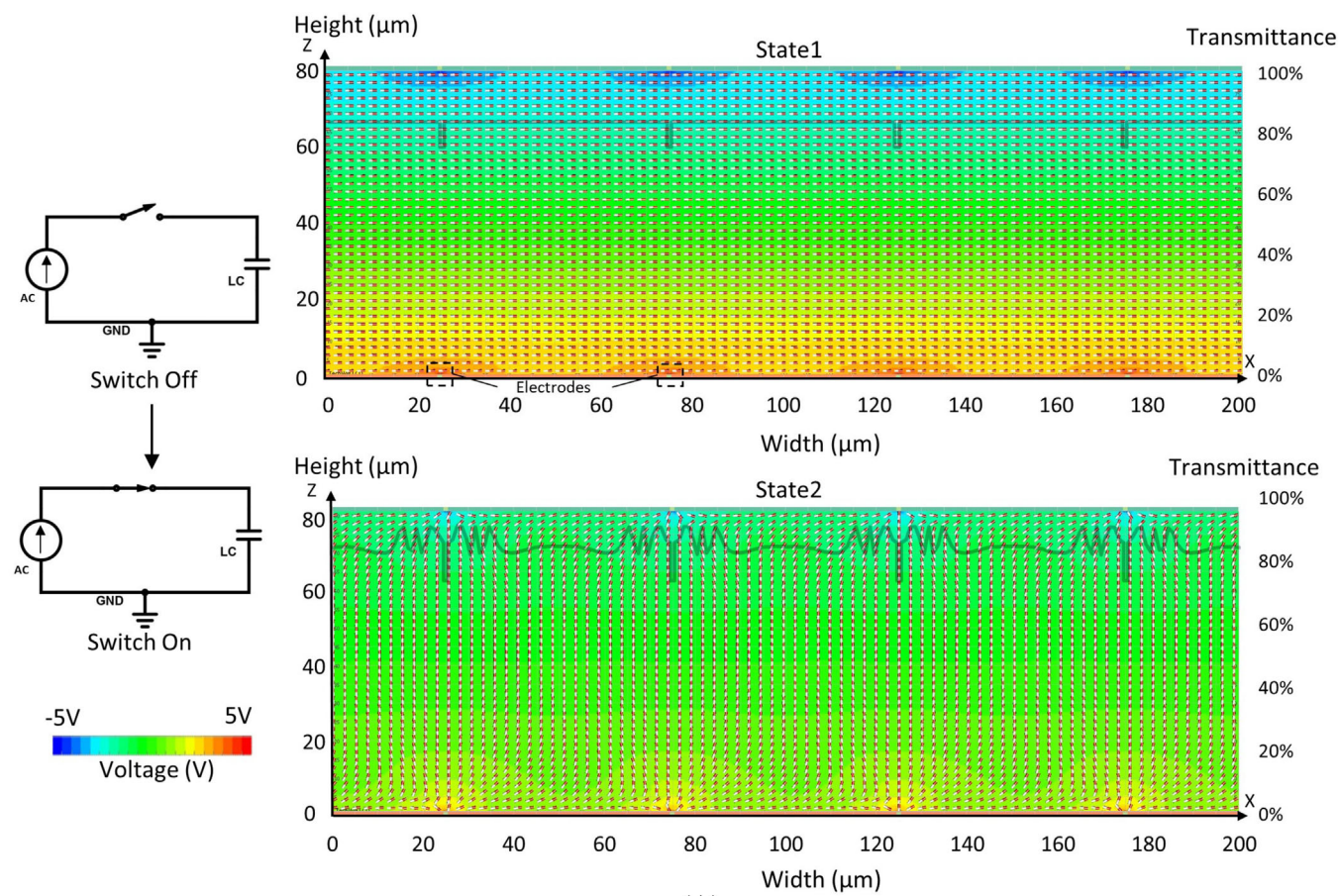
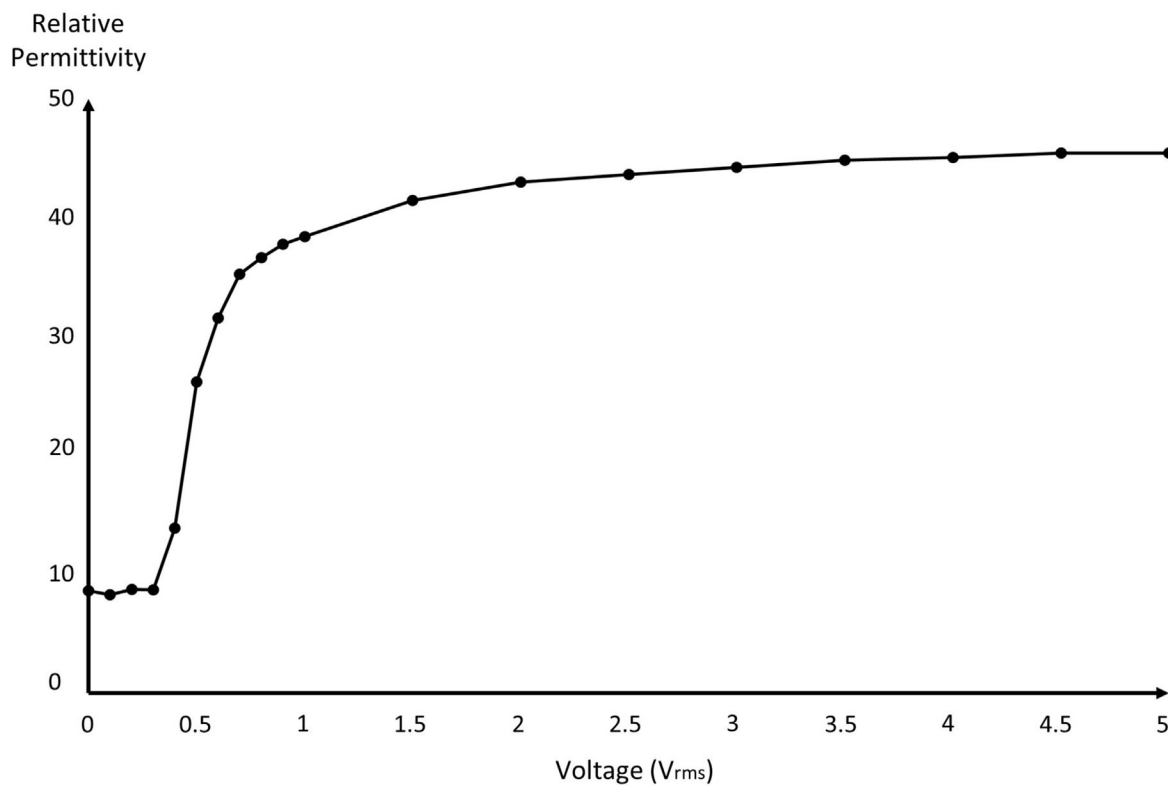


FIGURE 2 A, The surface current density on the antenna and the electric field intensity on the top surface when the LC director is planar aligned ($V = 0$). B, Specific absorption rate (SAR) simulation, demonstrating that the antenna is safe for near-eye operation. (C) Radiation pattern for two different liquid crystal states.



(A)



(B)

FIGURE 3 A, The electrode structure and Q-tensor simulation results of the liquid crystal layer. The LC substrate can be switched from state 1 to state 2. B, Plot of the Freedericksz curve for RDP-84909.

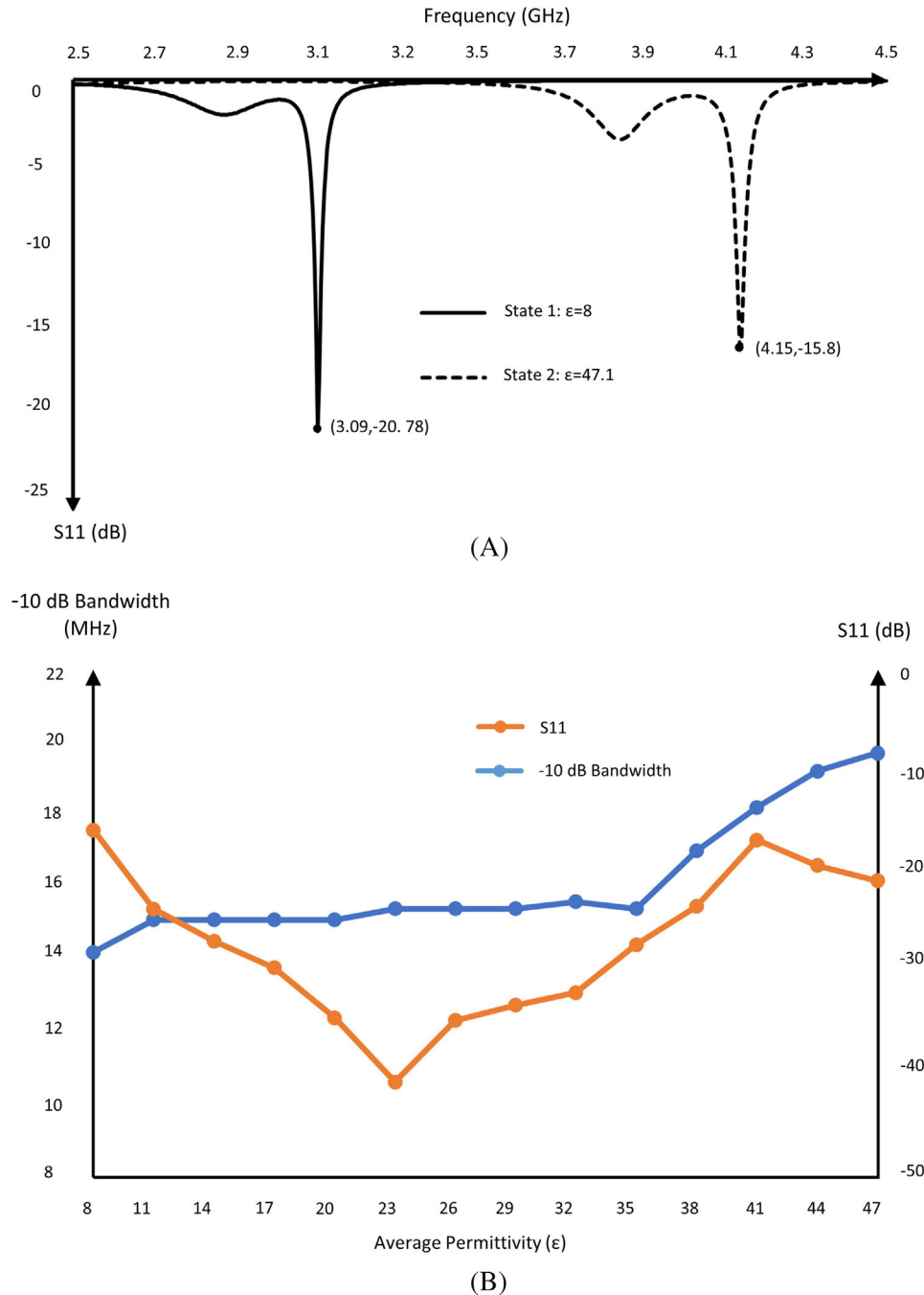
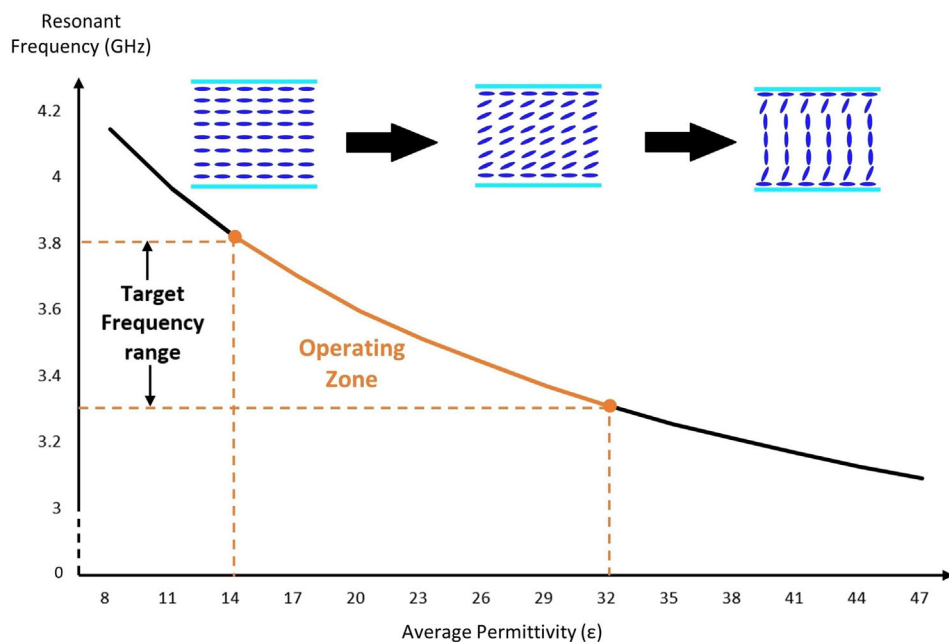


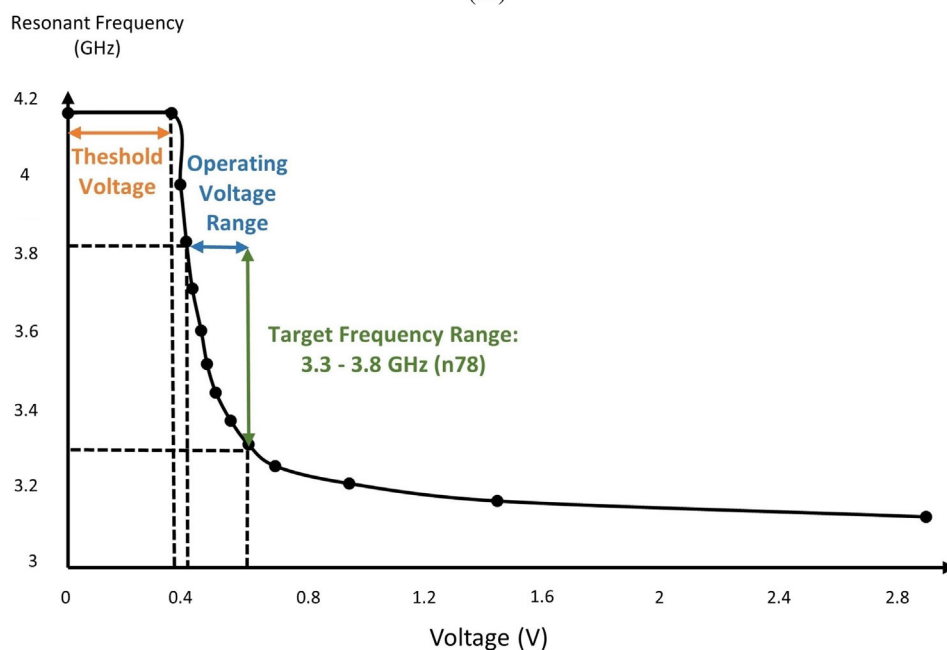
FIGURE 4 A, Plots of the S11 parameter of the antenna when the substrate is in two different states. This figure shows the theoretical maximum tunability. B, Plots of S11 and -10 dB bandwidth when the permittivity of the LC layer varies from 8 to 47. Therefore, the antenna could operate with the proposed variation of substrate permittivity.

Freedericksz curve, and the resonant frequency. In the antenna model, the substrate contains a dielectric layer and an LC layer, where we set the permittivity of the LC layer as variable, and thus obtain the frequency shift in response to this variation of permittivity. As shown in Figure 4A, when the average permittivity of the substrate increased from 8 to 47.1 (neglecting the anchoring effect to achieve maximum permittivity), the resonant

frequency shifted from 3.09 to 4.15 GHz, successfully covering the target frequency range n78 (3.3 to 3.8 GHz). The corresponding average permittivity varied from 14 to 32. Moreover, we also obtained -10 dB bandwidth versus different permittivity, as shown in Figure 4B. This curve illustrates that the -10dB bandwidths are within the range of 14.2 to 19.7 MHz, which ensures that data transmission is taking place efficiency and at an acceptable speed.



(A)



(B)

FIGURE 5 A, Average permittivity versus resonant frequency. This plot demonstrates that the antenna could cover the target frequency range (n78: 3.3–3.8 GHz). B, Plot of resonant frequency versus applied voltage. The driving voltage required to cover the target frequency ranges from 0.4 to 0.6 V.

Combining the Frederickz curve (previously shown in Figure 3B) with the relationship between applied voltage and resonant frequency (shown in Figure 5A), leads to the relationship between applied voltage and resonant frequency shown in Figure 5B. This figure shows the effect of varying the applied voltage from 0 to 3 V (since the antenna is designed for wearable applications), on the resonant frequency, resulting in a resonant frequency vari-

ation from 3.09 to 4.15 GHz. As mentioned previously, the target frequency range of this antenna design is from 3.3 to 3.8 GHz which is covered when the voltage is between 0.4 and 0.6 V, which is suitable for low power consumption wearable applications.

In Table 2, the specifications of our antenna are compared with previous tunable antenna designs. The table lists important parameters for assessing the performance

TABLE 2 Comparisons with previous work.

Reference	Antenna type	Antenna area (mm ²)	Frequency range (GHz)	Driving voltage (V)	Thickness of Substrate (μm)
[39]	Patch Antenna	1026.4	2.532–2.427	25	787
[40]	Patch Antenna	0.225	85–115	20	1020.2
[3]	Patch Antenna	400	4.84–5.12	-	300
[41]	Patch Antenna	612	2.02–2.4	-	500
[4]	Patch Antenna	434.7	2.7–2.9	-	500
This Work	Spiral Antenna	6.8	3.09–4.15	0.6	180

Target: 3.3 to 3.8

of the tunable antenna including antenna type, area, frequency range, driving voltage, and substrate thickness. Here, the driving voltage represents the voltage needed to tune the LC substrate. It is clear that our tunable antenna design has a smaller footprint, thinner substrate material, and lower driving voltage compared to other designs, and could potentially be used for wearable or implantable applications.

4 | CONCLUSION

In this paper, we have proposed a tunable centimeter wave antenna design for smart glasses applications. The antenna could be tuned from 3.3 to 3.8 GHz (FR1 n78 for 5G telecommunications applications) using 0.4 to 0.6 V. The theoretical maximum tunability of this design is 1.06 GHz (3.09–4.15 GHz), which could be achieved only when the anchoring effect is neglected. Compared with previous designs, this antenna requires a lower driving voltage, smaller area and demonstrates high tunability. This prospective design is suitable for wearable and implantable devices. The low driving voltage allows this tunable antenna to be used in low-power consumption and autonomous devices. The small area of the antenna could also enable its integration within a miniaturized design and its high tunability means that it can cover more frequencies and communicate with a wider range of devices in comparison with currently available designs.

Further work will focus on fabricating the antenna and developing the driving electronics for the reconfigurable surface. To fabricate the antenna pattern, laser printing or lithography techniques can be used, and glass spherical spacers would be used to control the thickness of the LC cell. The structure of the antenna and LC material will also be optimized to cover a wider bandwidth. Following this, the intention is to embed this antenna within a smart glasses system to expand the bandwidth allowing communication with multiple external devices, which will be of considerable benefit for IoT applications.

ACKNOWLEDGMENTS

The authors have nothing to report.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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How to cite this article: Y. Xia, M. Yuan, A. Dobrea, C. Li, H. Heidari, N. Mottram, R. Ghannam Reconfigurable wearable antenna for 5G applications using nematic liquid crystals. *Nano Select.* **2023**, *4*, 513.
<https://doi.org/10.1002/nano.202200209>