24 GHz Flexible LCP Antenna Array for Radar-based Noncontact Vital Sign Monitoring

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***Abstract*—Noncontact monitoring of human vital signs is an emerging research topic in recent years. A key approach to this monitoring is the use of the Doppler radar concept which enables real-time vital signs detection, resulting in a new class of radar system known as bio-radar. The antennas are a key component of any bio-radar module and their designs should meet the common requirements of bio-radar applications such as high directivity, circularly polarized and flexibility. This paper presents the design of a four-element antenna array on a flexible liquid crystal polymer (LCP) substrate of 100 μm thickness and ε_r of 3.35. The designed antenna array can be used with a 24 GHz bio-radar for vital signs monitoring in a non-contact manner. It features a compact size of 27.56 × 53 mm and relatively high gain of 6.17 dBi.**

I. INTRODUCTION

The measurement of physiological signals has important applications in the healthcare sector. The vital signs of interest in these applications often include heart rate (HR) and breathing rate (BR). Radar-based vital signs monitoring is a new technology that leads to the concept of *bio-radar* [1], which together with other flexible and wireless physiological sensors, promise to revolutionize the healthcare industry. It may be also used to detect life in search and rescue operations after disasters [2].

This concept uses Doppler radar to capture the BR and HR information in a contactless way. In a typical radar system, two antennas are used: one for the transmitter and another for the receiver. The transmitting antenna focuses the signal to the chest of the subject and the receiving antenna acquires the reflected signal, whose frequency changes due to micro-movements of subject's chest caused by breathing and heartbeat. This is known as the Doppler effect in which the received frequency increases or decreases as the target moves towards, or away from the radar, respectively [3].

One cycle of a heartbeat involves contracting and pumping blood through the circulation system between the heart and the rest of the body [4]. On the other hand, the respiration is a two-step quasi periodic activity which involves inhalation and exhalation [5]. The HR and BR information embedded in the received radar signal can be extracted using appropriate digital signal processing algorithm.

The antennas are a key component of any bio-radar module as transmission and reception of the signal with minimum losses is the key to a successful operation. They can compose of a single element or an array of multiple elements, can be designed for different frequencies, and use different types of substrates. However, their designs should meet the application requirements of the bio-radar, which include high directivity, circular polarization, flexibility, among others.

In this paper, a single antenna element (a.k.a. unit cell) on a flexible liquid crystal polymer (LCP) substrate for a 24 GHz bio-radar system is firstly designed. This is followed by the design of a 2- and 4-element array using the same unit cell to achieve better directivity and circular polarization performance for the bio-radar application.

The rest of this paper is organized as follows. Section II reviews the related works on antennas for radar applications. Section III presents the proposed antenna designs, including a unit cell and its 2- and 4-element arrays. Section IV discusses their simulated performance. Finally, Section V concludes the paper with some directions for future work.

II. RELATED WORKS

This section discusses related works on antenna designs for radar applications. The discussions are categorized by the radar's antenna requirements, namely frequency, polarization, directivity, and flexibility requirements.

A. Frequency: Radar modules can be designed for low, intermediate and high frequency. In [6], a circularly polarized 2×2 patch antenna array was implemented on low-temperature co-fired ceramic (LTCC) substrate and was integrated with a 60 GHz Doppler radar system. In [7], a 24 GHz millimeter wave antenna was designed to monitor the vital signs of patients who are immovable and in mental stress. A 915 MHz fractal antenna used with a low noise amplifier was proposed for continuous wave (CW) Doppler radar to monitor heart rate and breathing rate [8]. However, the use of low frequency limits the achievable antenna compactness and detection sensitivity when operating in a near-field condition.

B. Polarization: It is preferred to have a circularly polarized antennas as transmitter and receiver antennas signal can be easily isolated. This will also reduce higher order reflections and improve isolation from multiple reflections. Large ferrite device and circulator which are commonly used to isolate transmitter and receiver signal can thus be avoided. In [9], authors performed an analysis of circular polarization for bio-radar setup. Three antennas: one transmitter antenna that is right-hand circularly polarized (RHCP); and two receiver antennas, one RHCP and another left-hand circularly polarized (LHCP). The transmitted signal is reflected through a metallic reflector and the received signal is measured at both receiver antennas. It was found that the antenna pair with opposite polarization is more efficient than the pair with similar polarization. In [10], the authors proposed a signal reformation method that utilizes different antenna polarization. This was used to omit null detection point, which is a key challenge in contactless vital monitoring due to the noise generated by random body movements.

C. Directivity: Higher the antenna directivity or gain, higher the signal-to-noise ratio and more accurate measurement by the radar signals. In [13], the authors evaluated different 2.4 GHz antennas for vital signs monitoring, including patch, helical and Yagi-Uda antennas. The patch antenna exhibits a half-power beamwidth of 92° and a promising performance for vital signs detection. A helical antenna operating in axial mode at 2.4 GHz for a Doppler based CW radar is presented in [14]. It is an 8-turn design with on-reflector impedance matching to maintain the size. Compared to a conventional 2.4 GHz patch antenna, the helical design can offer a higher gain. However, the planar nature of the patch is attractive to achieving low profile and ease of fabrication using printed circuit board (PCB) technology. To improve directivity, multi-element array and higher operating frequency can be used by the patch design. For a given antenna size, a higher frequency narrows the beamwidth due to a larger size-to-wavelength ratio, resulting in higher directivity.

D. Flexibility: Flexibility is another upcoming property of the flexible circuits for next-generation consumer electronics. The materials used may include soft plastics, textiles, or even paper to make conformal antennas that can be easily integrated onto non-planar surfaces [15] such as spherical, cylindrical, and other complex shaped surfaces. In [16], the authors designed a 2.45 GHz wearable antenna using flexible material to measure human vital parameters. The materials include fabrics, telfon, rubber, and paper. In [17], the bending effects on a flexible ultra-wide band antenna on liquid crystal polymer substrate were studied. It demonstrated the antenna's ability to maintain its radiation pattern and gain performance under various bent conditions. However, these are wearable antennas that operate in near-field conditions. To the best of our knowledge, the flexibility feature has not been explored by bio-radar systems that operate in the far-field for vital sign monitoring.

The findings from the above literature review motivated us to propose a bio-radar antenna with the following features: (i) high operating frequency (24 GHz) for a compact design; (ii) circularly polarized for high isolation between transmitter/receiver signals; (iii) high directivity with low-profile using multi-element patch array design; and (iv) flexibility to allow mounting on non-planar surfaces such as curved walls and edges.

III. Proposed Antenna Designs

Any antenna array will require a unit element to be designed first. The unit element was designed to operate at 24 GHz with input impedance of 50 Ω on LCP substrate (Panasonic R-F705S) of 100um thickness and permittivity ϵ_r of 3.35. The proposed single-element unit cell consists of a monopole patch, a feed line, and metallic ground as shown in Fig. 1. The overall dimension of the unit cell is 20×16 mm. The length of the feed element is 3.125 mm which is a quarter of the signal wavelength for 24 GHz. The ellipse shaped radiating patch has a major axis radius of 4.33 mm and a major-to-minor axis ratio of 1.354. Two slots measuring 0.5×1.6 mm were cut on both sides of the horizontal ellipse. The dimensions were optimized to achieve the desired gain and circular polarization.

To further improve the gain and axial ratio of the circularly polarized antenna for remote vital sign monitoring, arrays using multiple unit cell elements were designed. The designed two-element array with overall dimension of 23×25.4 mm is shown in Fig. 2. The closest separation between the two elements is 1.3 mm. The feed line is a 50 Ω input, which is split into two 100 Ω lines to power each individual patch. Here, the T-shaped power divider is used along with a quarter wave transformer for impedance matching. Similarly, a four-element array is designed as shown in Fig. 3.

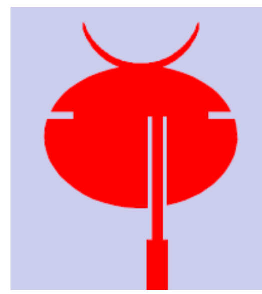


Fig. 1 Single-element unit cell

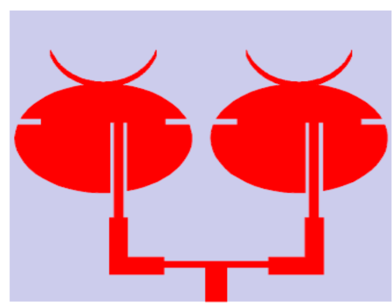


Fig. 2 Two-element array

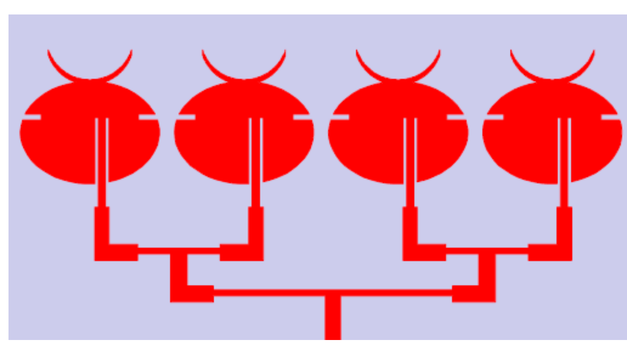


Fig. 3 Four-element array

IV. Results and Discussion

The proposed antennas in Section III are simulated using the Ansys High-Frequency Structure Simulator (HFSS). A wave port is provided to the center of each designed antenna for simulation. The antennas are evaluated in terms of their return loss, radiation pattern, gain, and axial ratio performances.

A. Return Loss

The return loss is a measure of the impedance mismatch between the feed line and antenna. The lower the return loss, the less amount of power is reflected and lost through impedance mismatch, and the more power is delivered to the antenna. Fig. 4 shows the simulated return loss $|S_{11}|$ for the proposed single element unit cell. It shows that the antenna achieves a return loss of approximately −16 dB at 24 GHz.

Fig. 5 and Fig. 6 shows an increasingly better return loss performance of −21.1 dB and −28.75 dB for the two-element, and four-element array, respectively. The latter also exhibits a −10 dB bandwidth of approximately 190 MHz.

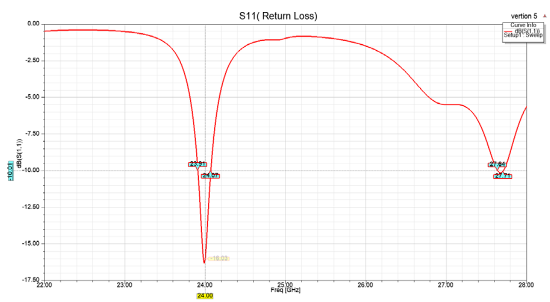


Fig. 4 Single element return loss $|S_{11}|$

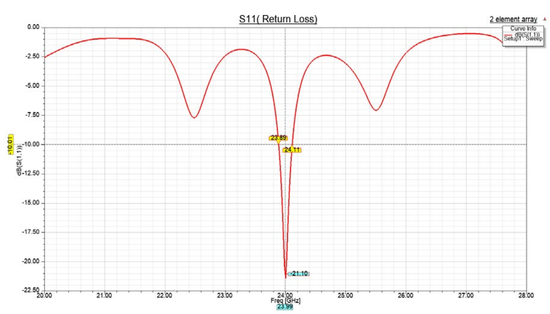


Fig. 5 Two-element array return loss $|S_{11}|$

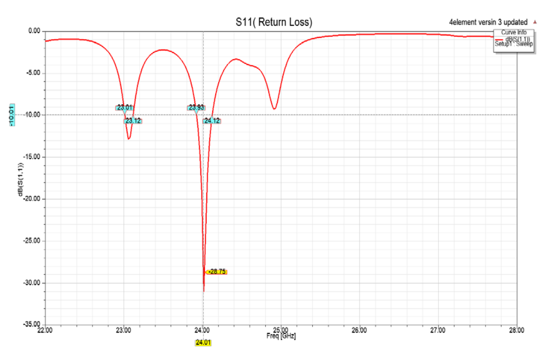
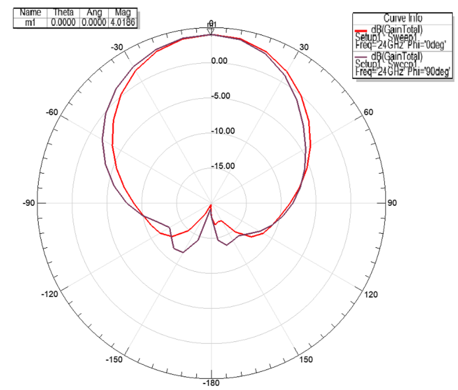


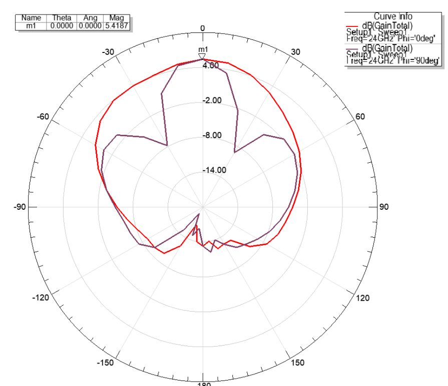
Fig. 6 Four-element array return loss $|S_{11}|$

B. Radiation Pattern

The radiation pattern depicts how the radiated signal from the antenna varies in different directions. Fig. 7 and Fig. 8 shows the simulated radiation pattern, and the corresponding 3D polar plot, respectively, for each antenna. It shows the maximum radiation intensity is in the direction of θ=0° for both element and array. Moreover, increasing the number of elements has the effect of narrowing the main beam.



(a)



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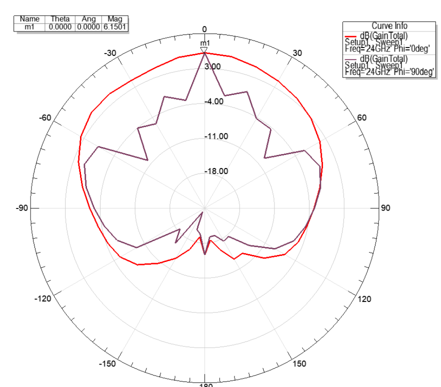
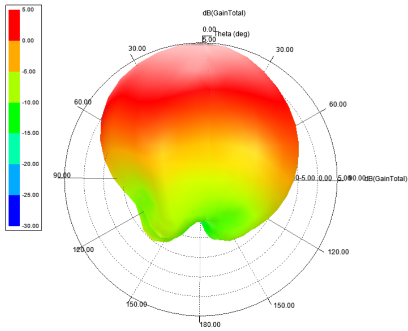
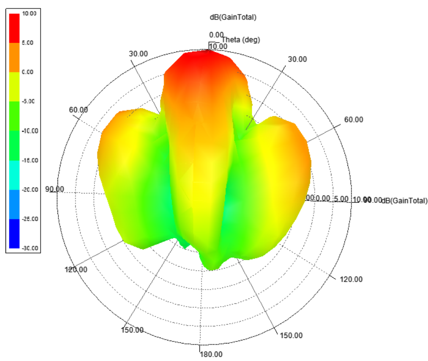


(c)

Fig. 7 Radiation pattern of (a) single-element unit cell; (b) two-element array; (c) four-element array. The plot for $\varphi=0^0$ and $\varphi=90^0$ refers to the E-plane (side-view) and H-plane (top-view), respectively



(a)



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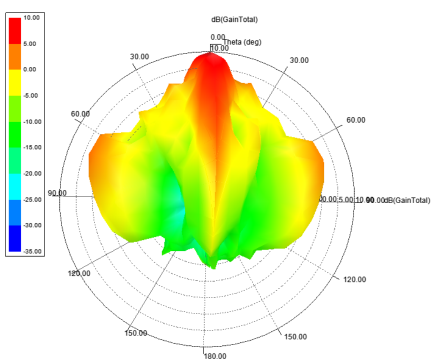
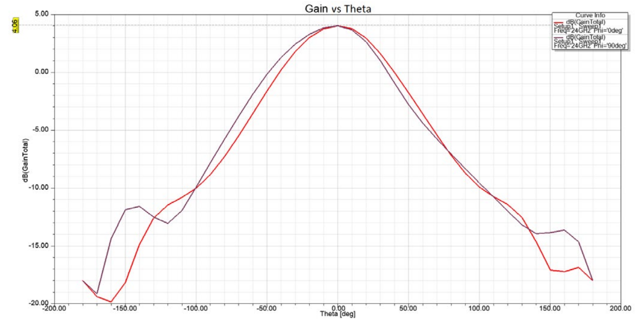


(c)

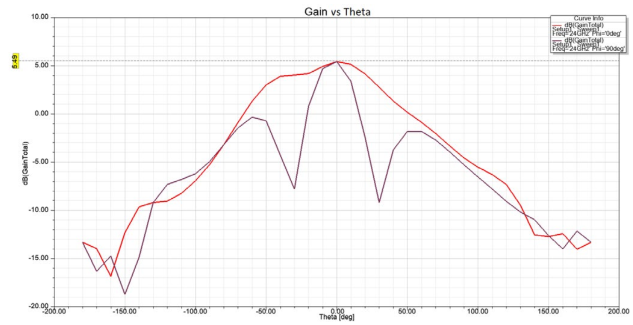
Fig. 8 3D polar plot for (a) single-element unit cell; (b) two-element array; (c) four-element array

C. Gain (Directivity)

The gain is a measure of the antenna's directivity or extent to which its signal propagates in the peak direction of radiation. The simulated gain on E-plane (φ=0°) and H-plane (φ=90°) as a function of theta (θ) at 24 GHz for each antenna is shown in Fig. 9. The results show a maximum gain of 4.09 dBi, 5.49 dBi, and 6.17 dBi, are achieved at θ=0° on both planes for single-element unit cell, two-element array, and four-element array, respectively. The achieved gain is attributed to the added horn type structure to the basic elliptical design.



(a)



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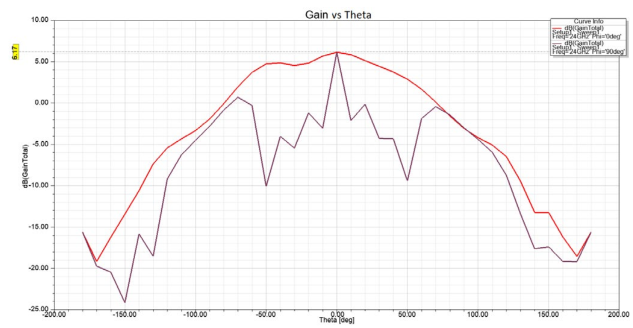


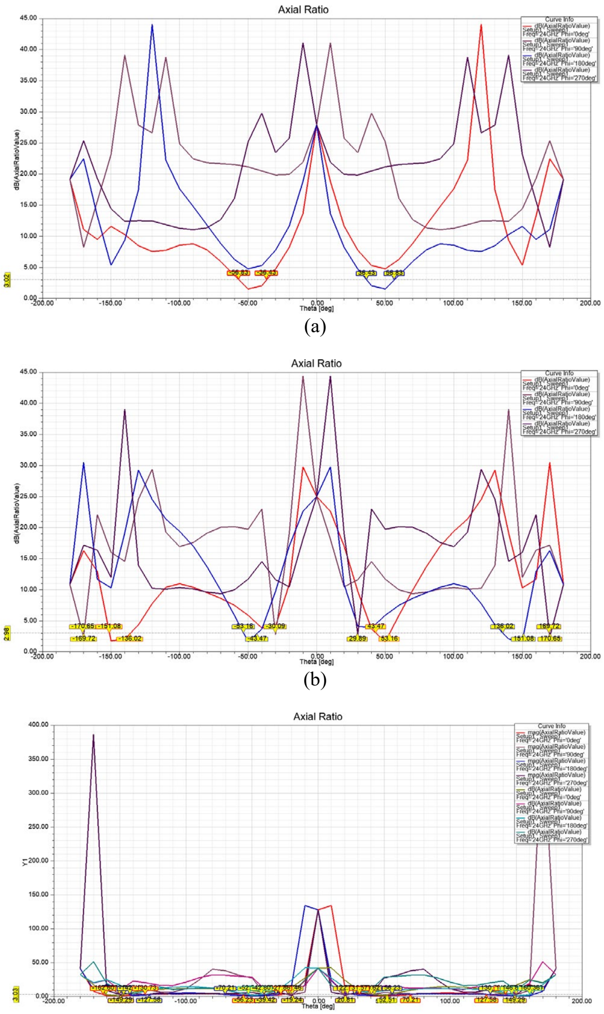
(c)

Fig. 9 Gain versus Theta (θ) for (a) single-element unit cell; (b) two-element array; (c) four-element array, with φ= 0^0 (red) and φ=90^0 (purple)

D. Axial Ratio

The axial ratio could measure how circularly polarized an antenna is. A perfectly circularly polarized antenna will have an axial ratio of 0 dB. However, an axial ratio of 3 dB or less is generally acceptable in practice. The proposed antennas are not fed from in between the ellipse, but rather towards the edge. This initiates two orthogonal modes (90° apart), which help to achieve circular polarization.

Fig. 10 shows the simulated axial ratio at different φ as a function of θ at 24 GHz for each antenna. The results show that an axial ratio ≤ 3 dB is achieved by each antenna for φ=0^0 and φ=180^0. Furthermore, the axial ratio is found to improve as the number of elements increases.



(a)

(b)

(c)

Fig. 10 Axial ratio vs Theta (θ) for (a) single-element unit cell; (b) two-element array; (c) four-element array

V. CONCLUSION

This paper firstly presents the design of a single-element unit cell that features an elliptical and horn shaped patch on flexible LCP substrate for 24 GHz bio-radar. The design of two- and four-element arrays using the same unit cell are then presented. The four-element array has the best simulated performance in terms of return loss, gain and axial ratio. It is flexible and thus can conform to the shape of any surface on which it is mounted. Future work includes an investigation into an accurate method of fabrication for this array, which has slot widths that are just a fraction of a millimeter. This will be followed by a performance characterization of the fabricated array and its use on an actual bio-radar module for noncontact vital sign monitoring.

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