

Polarization-Agile Antenna for Physiological Radar Monitoring Systems

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Abstract—In Doppler radar systems for human respiratory motion measurement, the change in wave polarization after reflection can be critical. In this contribution, a polarization-agile antenna based on a cavity-back slot fed by stripline is proposed to improve the experimental setup to investigate polarimetric effects in such measurements. The antenna consists of a series-fed sequentially-rotated array of four elements terminated in two ports. In this way, it is demonstrated that both right-handed and left-handed circular polarizations can be received and, by combination of both, arbitrary polarization can be obtained.

Index Terms—Antenna, Doppler, monitoring, polarization agility, radar, respiratory measurements, slot, stripline.

I. INTRODUCTION

After the COVID-pandemia, as people returned to offices, there was an increased awareness of how environmental conditions affect employee health and productivity. Occupancy and vital signs sensors can improve occupant health and provide sustainable solutions for buildings. Specifically, Doppler radar sensors offer accurate room-level occupancy detection for sedentary individuals without long delays or privacy concerns. These sensors are also affordable, easy to install, and have the added advantage of potential non-contact vital signs monitoring [1].

Compared to low-cost sensors that use passive infrared and ultrasound, other Doppler radar technology offers greater accuracy for stationary occupants. These sensors are easy to set

up without needing to worry about air vent placement, unlike ultrasonic sensors. Furthermore, Doppler radar sensors protect privacy more effectively than camera-based sensors. Most importantly, only Doppler radar technology can simultaneously provide both occupancy and vital signs data.

The precision of human respiratory motion measurements with Doppler radar depends on the strength of the reflected signal and the overall signal-to-noise ratio (SNR). The irregular characteristics of the human torso and its movements influence both the amount of returned signal and its polarization. For these reasons, the polarization change that suffers the reflected signal, with respect to the transmitted one, is unpredictable. In a recent study [2], [3] the performance of circularly polarized (CP) and linearly polarized (LP) antennas was evaluated for physiological radar, concluding that LP antennas consistently generate stronger return signals, while CP antennas do not significantly enhance SNR.

In any case, it is evident that receiving the signal with just one polarization, either linear or circular, is not optimal and probably leads to a decrease in the SNR. Due to the complexity of the target, the change in the polarization during reflection is not pure and part of the signal can have a different polarization than that being received. For these reasons, it is interesting to investigate the polarimetric radar effects in respiratory measurements. This can be done by, for instance,

using two LP antenna for both transmitting and receiving and rotating them 90° to measure the other polatization in 2x2 combinations.

However, this rotation, necessary to change the polarization of the antenna, might introduce some uncertainties. In this sense, having an antenna capable of generating a radiation pattern with any arbitrary polarization can facilitate the investigation on polarimetric radar effects in these kind of experiments.

When an antenna, whether a single element or an array, has two ports that can excite two orthogonal modes in the structure, it is possible to produce various polarization modes [4], [5]. In a corporate sequentially rotated array, using different feeds for each element of the array makes it straightforward to switch from circular polarization (CP) to linear polarization (LP), either horizontal or vertical, by turning off some of the radiating elements. However, this changes the array factor from CP to LP, resulting in different radiation properties, which is typically undesirable. Conversely, in a series-fed sequentially rotated array, either right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP) can be achieved by exciting one port of the antenna while terminating the other port with a matched load. LP can also be attained when the structure is excited by both ports simultaneously. Due to this capability and their simplicity in feeding, series-fed sequentially rotated arrays have been considered and implemented in this work. In [6], some of the authors proposed a polarization-agile antenna in microstrip technology, able to receive both LP (with any angle) and CP (Right-Handed-RH- & Left-Handed-LH-). This was achieved by designing a series-fed sequentially-rotated array of the so-called complementary strip-slot radiating elements ended in two ports. In this communication, we describe the concept of a polarization-agile antenna for physiological radar monitoring system.

II. CW DOPPLER RADAR WORKING PRINCIPLE

As illustrated in Fig. 1, the working principle of a single-tone CW radar for vital sign detection is as follows. The TX antenna transmits a single-tone signal in the direction of the human body. After reflection on it, the reflected signal is received by the RX antenna. Since the human torso is continuously moving, Doppler effect takes place and then the received frequency is shifted. The unmodulated RF signal $T(t)$ is generated by the waveform generator and transmitted by the TX antenna, separated from the human torso a distance d_0 :

$$T(t) = A_T \cos(\omega t + \theta(t)) \quad (1)$$

where ω is the carrier angular frequency, A_T is the power amplitude, and $\theta(t)$ is a random phase noise produced by the waveform generator. The time-varying displacement produced by the subject's chest movement is denoted as $x(t)$ and it

modulates the RF signal, so that the received signal at the radar RX antenna can be expressed as [7]:

$$R(t) \approx A_R \cos \left(\omega t - \frac{4\pi}{\lambda} (x(t) + d_0) + \theta \left(t - \frac{2d_0}{c} \right) \right) \quad (2)$$

where A_R is the received power, λ is the carrier wavelength, c stands for the speed of light in free space, $x(t)$ is the chest wall movement including respiration and heartbeat, and $\theta \left(t - \frac{2d_0}{c} \right)$ is the phase noise with a delay corresponding to twice the distance to the body (named d_0).

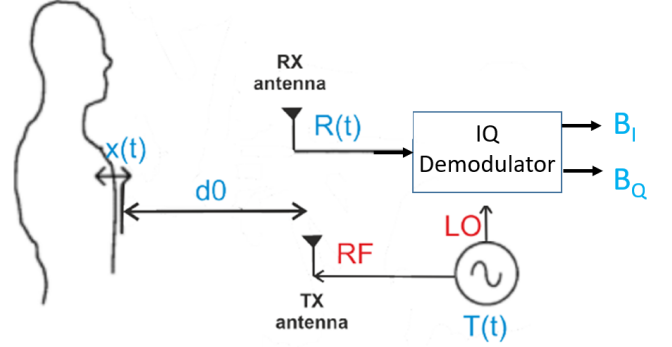


Fig. 1. Simplified block diagram of the Doppler-radar monitoring system.

When down-converting the reflected signal $R(t)$ to baseband $B(t)$ and splitting the received signal into I and Q channels, the baseband signals can be written as follows:

$$B_I(t) = A_I \cos \left(\frac{4\pi}{\lambda} (x(t) + d_0) + \Delta\theta(t) \right) + dc_I \quad (3)$$

$$B_Q(t) = A_Q \sin \left(\frac{4\pi}{\lambda} (x(t) + d_0) + \Delta\theta(t) \right) + dc_Q \quad (4)$$

(5)

where A_I and A_Q are the amplitudes of I/Q channels, dc_I and dc_Q are the DC offsets from the reflections from the surrounding stationary objects and circuit imperfections, and $\Delta\theta(t) = \theta(t) - \theta \left(t - \frac{2d_0}{c} \right) + \sigma$ is the residual phase noise plus σ , which stands for the phase shift produced in the reflection.

If the DC offsets are removed by calibration and the signals are normalized to remove the amplitude factors A_I and A_Q , by using arctangent demodulation, the subject's movement $x(t)$ can be recovered:

$$\arctan \left(\frac{B_Q(t)}{B_I(t)} \right) = \frac{4\pi}{\lambda} (x(t) + d_0) + \Delta\theta(t). \quad (6)$$

Please notice that $\Delta\theta(t)$ is negligible in coherent Doppler CW radar, due to range correlation effect [7]. Fig. 2 shows a comparison of received signals using vertically and horizontally polarized receive antennas for a vertically polarized transmit antenna. Significant signal levels can be clearly detected for both configurations.

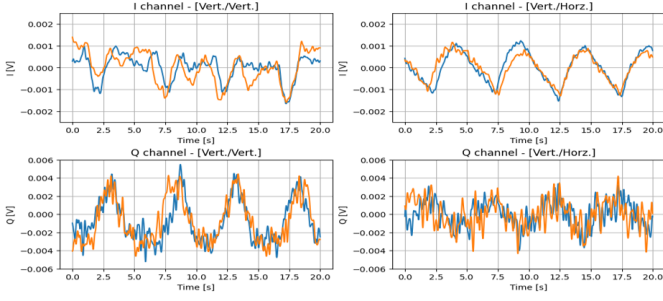


Fig. 2. Measurement example of received I and Q channels reflected from a seated human subject with antennas configured as Vertical TX & Vertical RX (a), Vertical TX & Horizontal RX (b). Note that significant signals are measured in both configurations, and in the case of the I-channel the cross-polarized signal (b) is actually larger than the co-polarized one (a).

III. PROPOSED CONCEPT

A polarization-agile antenna allows for adaptive switching to the optimal polarization for the best experimental condition.

A. Antenna Geometry

The antenna concept proposed in this contribution is a sequentially-rotated array of four radiating elements in planar technology terminated into two ports. Since it is a series-fed array, the feeding of the antenna is much simpler than in the case of a corporate array. The array element is a stripline-fed cavity-back slot that incorporate a stub that enables broad matching [8]. Although the radiating element is linearly polarized, circular polarization of the array is achieved by applying the sequential rotation technique [6], [9]. Fig. 3 shows the schematic of the antenna concept. As can be observed, if the antenna transmits/receives by port 1 (P1), the radiated/received wave has RHCP, whereas, by port 2 (P2), the wave polarization would be LH.

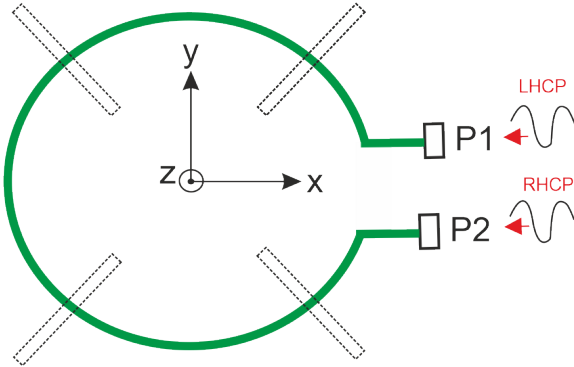


Fig. 3. Simplified schematic of the proposed antenna.

An example of the previously described array has been designed at 2.4 GHz. Thanks to the back cavity that the slot radiating element incorporates, the Front-to-Back Ratio (FBR) is almost 10 dB. Fig. 4 shows the gain radiation pattern obtained with the full-wave electromagnetic simulator ANSYS with the

co-polarization (in this case, LHCP) and cross-polarization (RHCP) components for the YZ-plane when the antenna is fed by P2. The array has an approximated peak gain of 5 dBi with excellent cross-polarization rejection at broadside (see Fig 4).

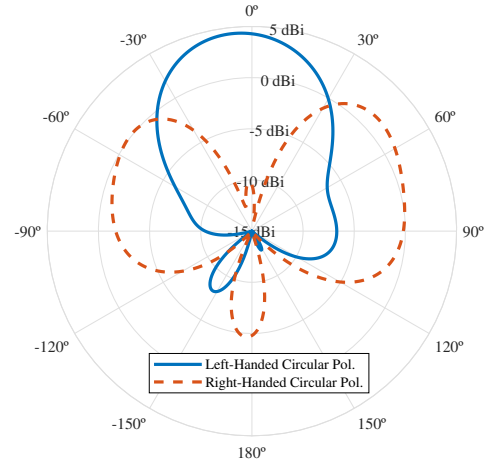


Fig. 4. Simulated gain radiation pattern in the YZ plane for the proposed antenna. Left-handed (LHCP) and right-handed circular polarizations (RHCP).

B. Arbitrary Linear Polarization

As combination of two circularly-polarized waves, a linear polarization with arbitrary angle can be obtained. Let's assume two CP waves with identical amplitude and different sign (RH and LH):

$$\vec{E}_1 = \cos(\omega t + \theta_1)\hat{x} + \sin(\omega t + \theta_1)\hat{y} \quad (7)$$

$$\vec{E}_2 = \cos(\omega t + \theta_2)\hat{x} - \sin(\omega t + \theta_2)\hat{y} \quad (8)$$

where θ_1 and θ_2 are arbitrary phase shifts. If these two waves are added, the total field can be written as follows

$$\vec{E}_T = [\cos(\omega t + \theta_1) + \cos(\omega t + \theta_2)]\hat{x} + [\sin(\omega t + \theta_1) - \sin(\omega t + \theta_2)]\hat{y}. \quad (9)$$

It is straightforward to prove that (9) can be conveniently written as

$$\vec{E}_T = 2 \cos\left(\frac{\theta_2 - \theta_1}{2}\right) \cos\left(\omega t + \frac{\theta_1 + \theta_2}{2}\right)\hat{x} + 2 \sin\left(\frac{\theta_2 - \theta_1}{2}\right) \cos\left(\omega t + \frac{\theta_1 + \theta_2}{2}\right)\hat{y}. \quad (10)$$

As can be seen, the two components of the fields are in phase; therefore, the resulting polarization is linear. It can be demonstrated that the angle of the LP with respect to the $\hat{x}$ -axis, ϕ , can be controlled with the phase shift difference between the two CP waves (i.e. $\Delta\theta_{21} = \theta_2 - \theta_1$):

$$\phi = \frac{\theta_2 - \theta_1}{2} = \frac{\Delta\theta_{21}}{2}. \quad (11)$$

C. Monitoring System

The proposal for the monitoring system is illustrated in Fig. 5. When transmitting with a conventional LP patch antenna (with any orientation), the reception antenna with the proposed concept allows the combination of the two received orthogonal CP waves that, when combined in a Digital Signal Processing (DSP) block, can receive an arbitrary polarization, as described in III-B.

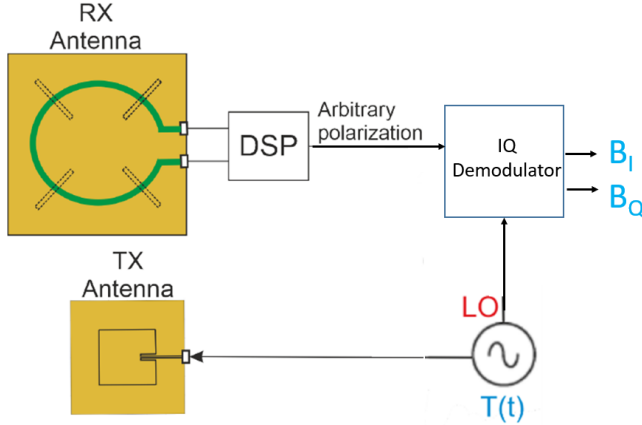


Fig. 5. Simplified block diagram of the proposed monitoring system.

IV. CONCLUSION

By using a polarization-agile antenna in the reception of the reflected signal coming from the human torso, polarimetric radar effects in respiratory measurements can be investigated in a more complete manner. Without any change in the experimental setup, different polarizations can be received via software. In this way, the best option for the critical SNR in these systems can be obtained in a very simple way. Additionally, if such an antenna is also used for transmission, any arbitrary combination of transmission-reception polarizations can be studied without the need of substituting or rotating the mounted antennas in the experimental setup.

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REFERENCES

- [1] C. Song, A. D. Droitcour, S. M. M. Islam, A. Whitworth, V. M. Lubecke, and O. Boric-Lubecke, "Unobtrusive occupancy and vital signs sensing for human building interactive systems," *Scientific Reports*, vol. 13, no. 1, Jan 2023.
- [2] J. Itokazu, M. Milijic, B. Jokanovic, O. Boric-Lubecke, and V. M. Lubecke, "Analysis of polarimetric radar effects in respiratory measurements," in *2024 IEEE International Microwave Biomedical Conference (IEEE MTT-S IMBioC)*, June 2024.
- [3] —, "Comparative performance assessment of circular and linear polarized antennas used for doppler radar measurement of respiratory motion," in *11th International Conference on Electrical, Electronics and Computer Engineering (IcETRAN)*, June 2024.
- [4] P. Rao and V. Fusco, "Polarisation synthesis and beam tilting using a dual port circularly polarised travelling wave antenna array," *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 150, pp. 321–324(3), October 2003.
- [5] K. F. Tong and J. Huang, "New proximity coupled feeding method for reconfigurable circularly polarized microstrip ring antennas," *IEEE Transactions on Antennas and Propagation*, vol. 56, pp. 1860–1866, 2008. [Online]. Available: <https://api.semanticscholar.org/CorpusID:44349209>
- [6] E. Abdo-Sánchez, C. Camacho-Peñalosa, J. Esteban, and T. M. Martín-Guerrero, "Planar multiband sequentially rotated array with polarisation agility based on the complementary strip-slot element," *Journal of Electromagnetic Waves and Applications*, vol. 29, no. 4, pp. 538–550, 2015.
- [7] A. Droitcour, O. Boric-Lubecke, V. Lubecke, J. Lin, and G. Kovacs, "Range correlation and i/q performance benefits in single-chip silicon doppler radars for noncontact cardiopulmonary monitoring," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 3, pp. 838–848, 2004.
- [8] A. Hernández-Escobar, E. Abdo-Sánchez, and C. Camacho-Peñalosa, "A broadband cavity-backed slot radiating element in transmission configuration," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 7389–7394, 2018.
- [9] J. Huang, "A technique for an array to generate circular polarization with linearly polarized elements," *IEEE Transactions on Antennas and Propagation*, vol. 34, no. 9, pp. 1113–1124, 1986.