Polarization-Converse Tag Design for Clutter-Isolation Radio Detection and Ranging Applications

Hao ZHANG¹, ², a) Jun-Qi Yang³

Abstract Radio detection and ranging (RADAR) always suffers from clutters, which extremely constrains its maximum operation distance. To mitigate such intrinsic and common problem, a novel polarization-converse tag on targets is proposed and designed with an integration of a shared-aperture dual-linearly-polarized (DLP) antenna, a microstrip hybrid coupler, and two RF grounded (GND) stubs, which can directly transform polarizations of transmitting interrogation (e.g., vertical polarization) to converse-polarization backscatters (e.g., horizontal polarization) insulated from clutters. The proposed polarization-converse tag design is validated by the theoretical analysis as well as experimental results, which brings a prospect for RADAR applications.

key words: Clutters, polarization-converse tag, DLP antenna, hybrid coupler, GND, radio detection and ranging (RADAR).

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

Radio detection and ranging (RADAR) technology has been recently developed for healthcare [1,2,3,4,5,6,7,8,9], e.g., fall detection [10,11,12], heartbeat detection [13,14], etc. Account of Doppler effects, both range and velocity can be monitored with an employment of modulated continuous wave to perform satisfactorily in detecting human gestures [15,16,17,18,19]. However, it always suffers from some environmental clutters to extremely constrain its maximum operation distance [20,21,22,23].

To mitigate such intrinsic and common problem, it is critical to insulate clutters and backscattered signal from targets with high isolation during radio detection and ranging procedures. Therefore, a novel polarization-converse tag is proposed with an integration of a shared-aperture antenna, a microstrip hybrid coupler, and two RF grounded (GND) stubs as demonstrated by Fig. 1. When base station interrogates the polarization-converse tag with vertical polarization, such interrogation (e.g., vertical polarization, VP) from RF power source can be captured by RX DLP antenna, and delivered to its VP port collocated with P₁ of hybrid coupler. Due to the special coupling properties, the total interrogation from the base station can accordingly be coupled and reflected by the hybrid coupler and two quarter wave-length (λ/4) open fan stubs (i.e., RF GND) to P₄ collocated with HP port of RX DLP antenna. Consequently, the employed hybrid coupler can converse such an interrogation from the vertically-polarized signals to horizontally-polarized ones, however still with Doppler effects insulated from the environmental clutters.

Fig. 1 The proposed clutter-isolation radio detection and ranging system with a polarization-converse tag (P₁: IN, P₂: DIR, P₃: COU, P₄: ISO).

In general, the metasurface is typically always the first choice for polarization-converter. It has lots of advantage like: wide frequency band [24][25][26], dynamical switch from linear-to-linear to linear-to-circular [23][24][26] etc. However, for RADAR to avoid the clutter, linear-to-linear polarization mode is enough, and compared with this work, the antenna periodical structure of metasurface is too big (230*250@ 7.9 and 8.2GHz in [24], 243*243@ 9.3 and 14.65GHz in [26]). Besides, the polarization conversion efficiency is also lower than this work which can reach 100% in theory.

To demonstrate operation scheme of the proposed polarization-converse tag, it is designed and fabricated on 20mil RO4350B (εᵣ=3.66, tanδ=0.0037) substrate. Meanwhile, 4 different ranges (d=30, 40, 50 and 60 cm) are experimented, which indicates that the backscattered signals from tag can be highly insulated with polarization converse.

Both theoretical analysis and experiment results validates...
the effectiveness of the proposed polarization-converse tag, which brings a prospect for RADAR applications.

2. Operation Mechanism

2.1 Analysis of Polarization Converse:
As illustrated by Fig. 1, two DLP antennas are implemented at both the base station and polarization-converse tag (terminal) to establish the wireless interrogation and backscatter links. To analyze the polarization converse, an RF signal with VP can be assumed as follow.

\[ V_s = a \cos \omega_o t \]  
(1)

where \( \omega_o \) is the operation fundamental frequency. Since both of two DLP antenna gains and the distance \( (d) \) are initially known, another RF signal propagated through the air to the incident \( (P_i) \) port of hybrid coupler can be approximated as referred to Friss equation [27].

\[ V_{in} = a \left( \frac{\lambda_0}{4\pi d} \right)^2 G^2 \cos \omega_o t \]  
(2)

Meanwhile the implemented hybrid coupler equips with special coupling properties [28], whose \( S \)-parameters are given below.

\[
S = \begin{bmatrix}
0 & -i & -1 & 0 \\
-i & \sqrt{2} & 0 & 1 \\
-1 & \sqrt{2} & 0 & -i \\
0 & 1 & -i & 0
\end{bmatrix}
\]  
(3)

Consequently, the signal \( (V_{in}) \) at incident port can be delivered to its direct (DIR) and coupled (COU) ports \( (V_{DIR} \text{ and } V_{COU}) \).

\[ V_{DIR} = -i a \left( \frac{\lambda_0}{4\pi d} \right)^2 G^2 \cos \omega_o t \]  
(4)

\[ V_{COU} = -a \left( \frac{\lambda_0}{4\pi d} \right)^2 G^2 \cos \omega_o t \]  
(5)

Due to two employed quarter wavelength \( (\lambda_0/4) \) open stubs, the reflection coefficient can be expressed with \( \Gamma = 1 \). Thus, the reflected signals at DIR and COU ports can be suppressed into hybrid coupler again, and distributed to IN and isolation (ISO) ports, which are approximated to (6) and (7).

\[ V_{IN}' = 0 \]  
(6)

\[ V_{ISO}' = ia \left( \frac{\lambda_0}{4\pi d} \right)^2 G^2 \cos \omega_o t \]  
(7)

As shown, all reflection at DIR and COU ports can be totally reflected to ISO port with IN one highly isolated. As referred to Friss Equation again [27], the signal received by HP port of DLP antenna at the base station can be expressed with

\[ V_s' = ia \left( \frac{\lambda_0}{4\pi d} \right)^4 G^4 \cos \omega_o t \]  
(8)

It should be noticed that the propagation coefficient from base station and polarization-converse tag can be defined with

\[ \kappa = \left| \frac{V_s'}{V_s} \right| = \left( \frac{\lambda_0}{4\pi d} \right)^2 G^2 \]  
(9)

The degradation from the propagation distance is consequently mitigated by gains of both DLP antennas. However, the leakage between VP and HP at the base station can seriously impact the polarization converse propagation coefficient once its operation distance is ultralong. Typically, such leakage can be evaluated by taken isolation \( (|S_{21}|) \) of TX DLP antenna into consideration. Therefore, it must satisfy such relation to avoid the signal leakage to ensure effectiveness of backscattered polarization-converse signal from the tag (terminal), as illustrated in Fig. 1.

\[ |S_{21}| \leq \kappa = \left( \frac{\lambda_0}{4\pi d} \right)^2 G^2 \]  
(10)

When DLP antenna is facilitated and tested, the isolation of VP and HP can be known. Consequently, the maximum operation distance \( (d) \) can then be obtained, and enhanced by improve the isolation between the VP and HP of the DLP antenna.

2.2 Procedure of DLP Antenna Design:
To validate the proposed polarization-converse tag for isolation -clutters RADAR applications, it is vital to design and fabricate the DLP antenna simultaneously with high gains and isolation. Hence, an air-substrate added DLP antenna is employed with coupled slots [29,30]. Therefore, the feed networks can be highly isolated from the huge ground copper (see Fig. 2c). Meanwhile, the hybrid coupler can therefore be directly connected to the feed networks (VP and HP ports) with compact structure for the polarization-converse tag facilitation. As demonstrated by Fig. 2, the detailed configurations of DLP antenna are provided.
The mentioned DLP antenna is designed and optimized in CST by achievement of both high gains and isolation at \( \omega_0=2.45\text{GHz} \). The low-loss, high-frequency substrate RO4350B is introduced with thickness of 20 mil. Moreover, the simulated and measured S-parameters as well as antenna gains are given in Fig. 3.

![Simulated (solid lines) and measured (dotted lines) results. (a) S-parameters. (b) gains at VP and HP ports of the DLP antenna.](image)

As illustrated, there are good agreements between the simulated and measured S-parameters of the DLP antennas, which are less than -10 dB at both HP and VP ports from 2.38 to 2.52 GHz and 2.38 to 2.50 GHz, respectively. Furthermore, the simulated and measured isolation between 2 ports can be achieved below -20 dB within frequency ranges from 2.38 to 2.52 GHz. The peak gains at HP and VP ports of the DLP antenna can both achieve their maximum values (8 dBi) and gain difference between two input ports is negligible, which demonstrates benefit for shared-aperture balanced DLP wave capture.

![Experimental results of different distances. (a) \( d=30 \text{ cm} \); (b) \( d=40 \text{ cm} \); (c) \( d=50 \text{ cm} \); (d) \( d=60\text{ cm} \).](image)

The calculated propagation coefficient (\( \kappa \)) as well as antenna isolation between VP and HP ports are provided in Fig. 5. It can be observed that the proposed polarization-converse tag directly transforms the polarizations of transmitting interrogation (e.g., vertical polarization) to converse-polarization backscatters (e.g., horizontal polarization) insulated from clutters. Furthermore, with an increase of the operation distances (\( d \)), the propagation coefficient (\( \kappa \)) decreases closely. As illustrated by the results, the presented polarization-converse tag has effective operation range, which is close to the calculated operation distance (\( d \)) by referred to (10). Consequently, to enhance the operation range, the isolation between both VP and HP ports should be carefully designed, which is an intrinsic issue in typical RADAR scenes. Such intrinsic problem can be solved by some other techniques, e.g., modulating interrogating signals, which is not a discussed topic in this research. However, the comparative experiments under different distances in Fig. 5 demonstrate an effectiveness of the proposed polarization-converse tag design, which highly insulates environmental clutters for further RADAR application.

### 3. Experimental Validation

To evaluate the proposed polarization-converse tag, a RF power source and a signal generator are employed as illustrated by Fig. 4. A HP signal is induced from the power source, and captured and converted by the polarization-converse tag through the air. Consequently, the adopted signal analyzer can measure another VP signal at the base station. Hence the propagation coefficient (\( \kappa \)) can be approximated by referred to (9) by considering both HP and VP signals. Meanwhile, four different ranges (\( d=30, 40, 50 \) and 60 cm) are experimented.

![Measurement setup (1441B signal generator is used for power source while 4037MB spectrum analyzer is used for signal analyzer).](image)

### 4. Conclusion

This work exploits a novel polarization-converse tag to mitigate an intrinsic problem of environmental clutters in radio detection and ranging (RADAR). With an integration of shared-aperture dual-linearly-polarized (DLP) antenna, hybrid coupler, and two RF grounded (GND) stubs, it can transform polarizations of transmitting interrogation (e.g., vertical polarization) directly to converse-polarization...
backscatters (e.g., horizontal polarization) insulated from clutters under different operation distances. Both theoretical analysis and experimental measurement validate the proposed polarization-converse tag, which brings a prospect for RADAR applications.

Acknowledgment

This work was supported in part by the Fundamental Research Funds for the Central Universities under Grant G2020KY0502, in part by the Basic Research Programs of Taicang, 2020, in part by the Basic Research Programs of Shaanxi Province, 2021 under Grant 2021JQ-125, in part by the Young Talent fund for Science and Technology in Suzhou, and in part by the National Natural Science Foundation of China through the Youth Program under Grant 62001395 (Corresponding author: Hao Zhang).

References

[1] L. Ren, Y. S. Koo, H. Wang, Y. Wang, Q. Liu and A. E. Fathy, "Noncontact Multiple Heartbeats Detection and Subject Localization Using UWB Impulse Doppler Radar," IEEE Microwave and Wireless Components Letters, vol. 25, no. 10, pp. 690-692, Oct. 2015.

[2] B. Wang, L. Guo, H. Zhang and Y. -X. Guo, "A Millimeter-Wave Radar-Based Fall Detection Method Using Line Kernel Convolutional Neural Network," IEEE Sensors Journal, vol. 20, no. 22, pp. 13364-13370, 15 Nov. 2020.

[3] G. Wang, C. Gu, T. Inoue and C. Li, "A Hybrid FMCW-Interferometry Radar for Indoor Precision Positioning and Versatile Life Activity Monitoring," IEEE Transactions on Microwave Theory and Techniques, vol. 62, no. 11, pp. 2812-2822, Nov. 2014.

[4] Park K, Jeong M J, Baek J J, et al. Analysis on frequency-dependency of conductive signal transmission channel for wearable devices[J]. IEICE Electronics Express, 2019: 16.201903588.

[5] Bhardwaj S, Lee D S, Mukhopadhyay S C, et al. Ubiquitous healthcare data analysis and monitoring using multiple wireless sensors for elderly person[J]. Sensors and Transducers, 2008, 90: 87-99.

[6] Lee H J, Lee S H, Ha K S, et al. Ubiquitous healthcare service using Zigbee and mobile phone for elderly patients[J]. International journal of medical informatics, 2009, 78(3): 193-198.

[7] Jung E Y, Kim J T, Sob J, et al. Development of U-healthcare monitoring system based on context-aware for knowledge service[J]. Multimedia Tools and Applications, 2015, 74(12): 2467-2482.

[8] Li M, Kim Y T. Development of patch-type sensor module for wireless monitoring of heart rate and movement index[J]. Sensors and Actuators A: Physical, 2012, 173(1): 277-283.

[9] Wang L H, Dong W Z, Chen J Z, et al. Low-power low-data-loss bio-signal acquisition system for intelligent electrocardiogram detection[J]. IEICE Electronics Express, 2015: 14.20151142.

[10] P. Youngkong and W. Panpanyatap, "A Novel Double Pressure Sensors-Based Monitoring and Alarming System for Fall Detection," 2021 Second International Symposium on Instrumentation, Control, Artificial Intelligence, and Robotics (ICA-SYMR), 2021, pp. 1-5, doi: 10.1109/ICA-SYMP50206.2021.9358439.

[11] Singh, Amuradha, et al. "Sensor technologies for fall detection systems: A review." IEEE Sensors Journal 20.13 (2020): 6889-6919.

[12] Yacchirema, Diana, et al. "Fall detection system for elderly people using IoT and ensemble machine learning algorithm." Personal and Ubiquitous Computing 23.5 (2019): 801-817.

[13] P. Kontou, S. B. Smida, M. Dragone, S. Nikolau and D. E. Anagnostou, "CW Radar Based System with Automated DC Offset Reduction for Heartbeat Detection," 2020 IEEE USNC-CNC-URSI North American Radio Science Meeting (Joint with AP-S Symposium), 2020, pp. 73-74, doi: 10.23919/USNC/URSI49741.2020.9321670.

[14] Q. Jian, J. Yang, Y. Yu, P. Björkholm and T. McKelvey, "Detection of breathing and heartbeat by using a simple UWB radar system," The 8th European Conference on Antennas and Propagation (EuCAP 2014), 2014, pp. 3078-3081, doi: 10.1109/EuCAP.2014.6902477.

[15] L. Aouchiche, L. Ferro-Famil and J.-P. Ovarlez, "New Doppler Processing for the Detection of Small and Slowly-Moving Targets in Highly Ambiguous Radar Context," 2020 17th European Conference on Antennas (EuRAD), 2021, pp. 46-48, doi: 10.1109/EuRAD48048.2021.00023.

[16] Bao X, Zhan Y, Xu C, et al. A novel dual microwave Doppler radar based vehicle detection sensor for parking lot occupancy detection[J]. IEEE Antennas Express, 2016: 13.20161087.

[17] Liu W K, Fu H P, Yang Z K. A Doppler radar vital sign detection system using concurrent dual-band hybrid down conversion architecture[J]. IEEE Antennas Express, 2016: 16.20190665.

[18] Yang Z K, Zhao S, Huang X D, et al. Accurate Doppler radar-based heart rate measurement using matched filter[J]. IEEE Electronics Express, 2020, 17(8): 20200062-20200062.

[19] Sakamoto T, Inasaka R, Taki H, et al. Accurate heartbeat monitoring using ultra-wideband radar[J]. IEEE Antennas Express, 2015: 12.20141197.

[20] Yang J, Wang R, Shi Y, et al. Dual-use multistatic HF ocean radar for current mapping and ship tracking[J]. IEEE Electronics Express, 2014: 11.20140281.

[21] Niu, Y. Sun, Y. Li and Y. Deng, "Study and Analysis on the Nonlinear Modeling of the Environmental Clutter," 2012 2nd International Conference on Remote Sensing, Environment and Transportation Engineering, 2012, pp. 1-3, doi: 10.1109/RSETE.2012.6260738.

[22] L. Yujie, W. Wenguang and S. Jinping, "Research of Small Target Detection within Sea Clutter Based on Chaos," 2009 International Conference on Environmental Science and Information Application Technology, 2009, pp. 469-472, doi: 10.1109/ESIAT.2009.60.

[23] Sun S, Jiang W, Gong S, et al. Reconfigurable linear-to-linear polarization conversion metasurface based on PIN diodes[J]. IEEE Antennas and Propagation Letters, 2018, 17(9): 1722-1726.

[24] Gao X, Yang W L, Ma H F, et al. A reconfigurable broadband polarization converter based on an active metasurface[J]. IEEE Transactions on Antennas and Propagation, 2018, 66(11): 6086-6095.

[25] Lévesque, Quentin, et al. "Plasmonic planar antenna for wideband and efficient linear polarization conversion." Applied Physics Letters 104.11 (2014): 111105.

[26] Zheng Q, Guo C, Ding J. Wideband metasurface-based reflective polarization converter for linear-to-linear and linear-to-circular polarization conversion[J]. IEEE Antennas and Wireless Propagation Letters, 2018, 17(8): 1459-1463.

[27] Gu, W. Lin, S. Henour and K. Wu, "Readout Distance Enhancement of Battery-Free Harmonic Transponder," IEEE Transactions on Microwave Theory and Techniques, vol. 69, no. 7, pp. 3413-3424, July 2021.

[28] H. Zhang, S. Gao, W. Wu and Y. Guo, "Uneven Power Loss Bio-signal Based Vehicle Detection Method Using Line Kernel Convolutional Neural Network," IEEE Antennas Express, 2016: 13.20161087.