Ultra-wideband and large-range incident angles radar cross-section reduction by quasi-fractal polarisation conversion metasurfaces

Amir Hossein Shakouri,1 Edris Ameri,2 and Seyed Hassan Sedighy3,✉
1Electrical Department, Beheshti University, Tehran, Iran
2Electrical Engineering, Iran University of Science and Technology, Tehran, Iran
3School Advanced Technologies, Iran University of Science and Technology, Tehran, Iran
✉Email: sedighy@iust.ac.ir

Introduction: During recent decades, microstrip structures ranging from radio frequency (RF) and microwave circuits to radiation and scattering structures have come into vogue [1–4]. Nowadays, 2D surfaces composed of sub-wavelength periodic unit cells have engaged many researchers. Such 2D periodic unit cells that are called metasurfaces have some features that we may rarely find or cannot find in nature. Due to rapid developments of the radar technology, hiding from eagle eyes of radars have been considered more than before [5, 6]. Although the geometrical-shaping method of the vehicles can be considered as a solution to minimise radar cross-section (RCS) by redirecting scattered waves, it imposes some constraints on the vehicle shape that is undesirable, especially in the case of flying objects in which aerodynamics property is very critical. Recently, metasurfaces have been proposed for RCS reduction (RCSR) as an effective solution. These metasurfaces can be categorised into two groups: Phase cancellation mechanism by using two different artificial magnetic conductors unit cells with 180 ± 37 degrees reflection phase differences [7–11], and polarisation conversion mechanism by using rotated counterparts polarisation conversion metasurfaces [12, 13].

In this study, a new quasi-fractal metasurface is proposed to improve the bandwidth and their oblique incident response of polarisation conversion metasurfaces (PCMs) surface and RCSR consequently for hiding from eagle eyes of radars. The RCSR bandwidth of the proposed metasurface that is implemented on a very thin, low cost, and commercially available FR-4 substrate is higher than the early published studies such as [12, 13]. In addition, 10-dB RCSR bandwidth of the surface for 40 degrees oblique incident is significantly better than the state-of-the-art studies such as [9]. The 10-dB RCSR bandwidth of the proposed PCM is from 7.68 to 40.87 GHz (136.73%) for normal incident waves and more than 96.7% up to 40 degrees incident angle that verifies the large range incident angle RCSR of the surface. The experimental measurement results at the normal incident angle and their comparison with simulation ones prove the idea.

Fig 1 (a) Top and side view of the double-heads arrow quasi-fractal polarisation conversion metasurface (PCM) unit cell

Koch fractal and circles increase the effective electrical lengths in the PCM unit cell and excite more Plasmon resonance frequencies that improve the bandwidth polarisation conversion of the unit cell accordingly.

The proposed metasurface demonstrates 10-dB RCSR from 7.68 to 40.87 GHz (136.73%) for normal incident waves, and more than 96.7% up to 40 degrees incident angle that verifies the large range incident angle RCSR of the surface. The experimental measurement results at the normal incident angle and their comparison with simulation ones prove the idea.
Fig 2 (a) The proposed quasi-fractal PCM unit cell and its mirrors, (b) schematic of the proposed quasi-fractal PCM tiles with its 90, 180, and 270 degrees rotated ones

Fig 3 The co- and cross-polarisation reflections of the infinite periodic unit or its mirror

32.62 and 38.04 GHz where polarisation conversion efficiency is approximately 100%.

The proposed unit cell surface current distributions are depicted in Figure 4 for various angles of rotation (0, 90, 180 and 270 degrees) at $f = 19.5$ GHz, which has good PCM efficiency. As expected from previous discussions, the surface current on 0 and 180 degrees rotated cells have an opposite current component along the x-axis, while they have an in-phase current component along y-axis. Therefore, it can be concluded that one part of the reflected waves (along x) cancel out each other, while the other one (along y) are added in-phase. A similar argument can be explained for 90 and 270 degrees rotated cells. Therefore, this unit cell with its mirrors can be used for PCM RCSR in the arrangement as shown in Figure 2(b).

**Design, simulation and experimental results:** The proposed quasi-fractal PCM surface is fabricated as shown in Figure 6. This surface consists of the proposed quasi-fractal PCM with three 90, 180, 270 degrees rotated ones arranged in $3 \times 3$ tiles array. The monostatic RCSR of the proposed surface for the different incident angle is shown in Figure 5 at both TE- and TM-incident polarisations, which prove more than 96.7% and 78% 10-dB RCSR bandwidth for TE- and TM-polarisations, respectively, up to 40 degrees incident angle.

The simulation results depict more than 10-dB RCSR from 7.68 to 40.87 GHz (136.73%) for the normal incident and something about (90.7%) for 40 degrees oblique incident.

The simulation results are verified for the normal incident by a simple experimental set-up for RCS measurement, and both of them have been shown for better comparison in Figure 7. The best performance of the proposed PCM is obtained at 33 GHz with more than 40 dB RCSR.

It should be noted that due to the limitation of measuring instruments, we can only measure the RCSR of the PCM from 7 to 33 GHz. As it can be observed, there is a good correspondence between simulation and measurements that proves the idea. Notice that some difference between

Fig 4 The surface current distribution for various angles of rotation at $f = 19.5$ GHz. (a) 0 degrees, (b) 90 degrees, (c) 180 degrees, (d) 270 degrees TE polarisation incident wave

Fig 5 The monostatic radar cross-section reduction (RCSR) of chessboard configuration for different incident angle (a) TE incident polarisation, (b) TM incident polarisation
The proposed metasurface performance is compared with the state-of-the-art references in Table 1. It can be observed that the RCSR bandwidth of this structure is significantly better than those introduced in other studies. It should be mentioned that the proposed metasurface is implemented on low-cost commercially available FR-4 substrate, while the other references are implemented on expensive ones as tabulated in the table excluding [11] that has significantly lower RCSR bandwidth.

### Table 1. The performance comparison of the proposed quasi-fractal polarisation conversion metasurface with state-of-the-art references ($\lambda_c$: Free-space wavelength at the centre frequency)

| Structure          | Thickness (mm) ($h/\lambda_c$) | Normal incident (%) | Oblique incident (%) | Substrate          |
|--------------------|---------------------------------|---------------------|----------------------|--------------------|
| [7]                | 2.28(0.124)                     | 85.9/4.23.28        | not reported         | RO4003             |
| [10]               | 6.35(0.146)                     | 91.3/7.5–10         | 31% (40°)            | RT/daroid-5880     |
| [8]                | 1.27(0.079)                     | 42/14.8–22.7        | 18.4% (40°)          | RO3010             |
| [9]                | 6.80(0.164)                     | 95/3.8–10.7         | 30% (40°)            | RO4003 & PTFE       |
| [11]               | 2.5(0.246)                      | 108/13.6–45.5       | 109% (40°)           | FR-4&Air           |
| [12]               | 1.5(0.147)                      | 84.7/7/17–42       | -                    | F4B-2              |
| [13]               | 2.5(0.204)                      | 126.5/9.4          | 67.5% (40°)          | FR-4&Air           |
| This study         | 2.5(0.202)                      | 136.7/7.68–40.87   | 90.7% (40°)          | FR-4&Air           |

**Note:**
- The proposed metasurface was designed based on polarisation conversion concept to achieve ultra-wideband RCSR. The simple and low-cost proposed metasurface is composed of double-heads arrowed-like unit cell that benefited from the second iteration Koch fractal in its arm and cut-line in order to broaden the bandwidth. The unit-cell and its 90, 180 and 270 degrees rotated counterparts obtain destructive interference cancellation between their reflected waves. The designed metasurface depicts a good performance in RCSR larger than 10-dB from 7.68 to 40.87 GHz, 136.73% fractional bandwidth.

© 2021 The Authors. *Electronics Letters* published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Accepted: 9 January 2021
doi: 10.1049/ell2.12094

---

**References**

1. Pozar, D. M.: *Microwave Engineering* (4th ed.), Wiley, New York (2011)
2. Ramanujam, P., et al.: Design of miniaturized super wideband printed monopole antenna operating from 0.7 to 18.5 GHz. *Int. J. Electron. Commun.* 123, 153273 (2020)
3. Ramanujam, P., et al.: Design of compact patch antenna with enhanced gain and bandwidth for 5G mm-wave applications. *IET Microwaves Antennas Propag.* 14(12), 1455–1461 (2019)
4. Veluchamy, L., Alsaith, M. G. N., Selvan, K. T.: Design and evaluation of a wideband reflectarray antenna using cross dipole with double-ring elements. *Int. J. RF Microwave Comput. Aided Eng.* 29(9) (2019)
5. Holloway, C. L., et al.: An overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials. *IEEE Antennas Propag. Mag.* 54(2), 10–35 (2012)
6. Knott, E. F., Schaeffer, J. F., Tulley, M. T.: *Radar Cross Section* (2nd ed.). SciTech Publishing, Raleigh, North Carolina (1995)
7. Esmaeili, S. H., S. H. Sedighy: Wideband radar cross-section reduction by AMC. *Electron. Lett.* 52(1), 70–71 (2016)
8. Inarte, J. C., et al.: Broadband radar cross-section reduction using AMC technology. *IEEE Trans. Antennas Propag.* 61(12), 6136–6143 (2013)
9. Haji-Ahmadi, M. J., et al.: Pixelated checkerboard metasurface for ultra-Wideband radar cross section reduction. *Sci. Rep.* 7(1) (2017)
10. Modí, Anuj Y., et al.: Novel design of ultra-broadband radar cross section reduction surfaces using artificial magnetic conductors. *IEEE Trans. Antennas Propag.* 65(10), 5406–5417 (2017)
11. Ameri, Edris, Esmaeili, S.H., Sedighy S.H.: Low cost and thin metasurface for ultra wide band and wide angle 2 polarization insensitive radar cross section reduction. *Appl. Phys. Lett.* 112(20), 201601 (2018)
12. Chen, H.Y., et al.: Ultra-wideband polarization conversion metasurfaces based on multiple plasmon resonances. *Appl. Phys. Lett.* 115, 154504–154504-5 (2014)
13. Ameri, Edris, Esmaeili, S.H., Sedighy S.H.: Ultra wideband radar cross section reduction by using polarization conversion metasurfaces. *Sci. Rep.* 9(1) (2019)
14. Yin, Jia Yuan, et al.: Ultra wideband polarization-selective conversions of electromagnetic waves by metasurface under large-range incident angles. *Sci. Rep.* 5(1), 12476 (2015)