Millimeter-Wave Retro-Directive Frequency Coded Lens by Curved One-Dimensional Photonic Crystal Resonator

ALI ALHAJ ABBAS, YAMEN ZANTAH, (Graduate Student Member, IEEE), ASHRAF ABUELHAJA, AND THOMAS KAISER, (Senior Member, IEEE)

1 Institute of Digital Signal Processing, University of Duisburg-Essen, 47057 Duisburg, Germany
2 Department of Electrical Engineering, Applied Science Private University, Amman 11931, Jordan

Corresponding author: Ali Alhaj Abbas (ali.alhaj-abbas@uni-due.de)

This work was supported in part by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Project 287022738-TRR 196 and Project S04, and in part by the European Regional Development Fund (ERDF) through the Project Terahertz-Integrationszentrum (THzlZ) under Project EFRE-0400215.

ABSTRACT Innovating passive and chipless coded landmarks have recently emerged for high accuracy self-localization systems. Existing landmarks make use of the combination of retro-directive devices, corner reflectors and lenses, with a coding particle in order to give a high RCS response over a wide angle. In this paper, with a consideration of important practical parameters unappreciated in existing designs, we propose a wide-angle retro-directive frequency-coded lens based on a curved one-dimensional Photonic Crystal (PhC) resonator. The proposed frequency-coded lens is made of two parts: a homogenous lens and a curved PhC resonator where the resonator is located along the lens focal line. A frequency coding is used, where the presence or absence of a notch frequency in a specified information channel encodes an information bit. A PhC resonator provides unique advantages over existing coding particles due to its continuity along the lens focal line which creates a stable ID appearance over wide-angle. In addition, the potential of coding in its volume, rather than on the surface, allows for a high coding capacity. Two frequency-coded lenses with single and dual defect resonators are EM simulated, fabricated, and experimentally validated in the W-band (75 GHz-110 GHz). Simulated results show that a wide detection angle of 170° can be achieved where the tag ID is maintained over all angles. A wide retro-directivity of 80° and 60° is experimentally demonstrated for frequency-coded lenses by a single defect (single notch) and a dual defect (double notch) PhC resonator, respectively.

INDEX TERMS One-dimensional photonic crystal resonator, homogenous lens, radar cross section (RCS), RFID, coded reflectors.

I. INTRODUCTION Attaining fully automated and robotized systems in the industrial world entails the implementation of highly accurate self-localization, e.g., for flying robots. Indoor localization systems are growing up as a key element to overcome the shortcoming of existing satellite-based radio technology, such as GPS, in operating in indoor environments.

Contemporary indoor positioning methods can instead operate with existing wireless infrastructure based on various radio technologies like Bluetooth, WiFi, and Radio Frequency IDentification (RFID) [1], [2]. Since these technologies use the lower microwave spectrum, limited localization accuracies in the cm range can only be achieved. Even with the high employed frequencies in 5G systems, below cm-accuracy is not approachable [3]. For low-cost infrastructures, [4], [5], localization based on asynchronous chipless RFID technology, rather than chipped, surpasses
other radio technologies [6], [7]. On the other hand, high localization accuracy is allowed by exploiting high mm-Wave (e.g., W-band) or THz band since a superior time resolution can be achieved, thanks to exceptionally large bandwidths [8].

Substantially, a self-localization or device-based localization can be described by an object equipped with an RF reader which relies on coded landmarks to locate itself, see Figure 1. Coded landmarks (also called beacons or reference nodes) are distributed at fixed and known positions in an indoor area. Tags placement in terms of their positions and orientations is pre-optimized for a specific area in order to provide maximum coverage [9]. For a low-cost infrastructure, these landmarks should be passive, which operate without a power supply, and also chipless, which need no chip technology to be produced. Each tag should have a unique ID employing frequency coding where each tag should selectively react at a certain dedicated frequency by introducing a peak or a notch.

Innovative landmarks are required for a reliable operation of such a system. These landmarks should be designed to have a high coding capacity where several tags can be uniquely identified. High coding capacity is essential for achieving high accuracy and also increasing the coverage zone in which more tags can be reached by the reader [9]. Retro-directivity is a very important parameter since the reader may reach the tag under a wide range of incidence angles which have to be supported by the tags. Moreover, to allow long-range communication between the reader and tags, tags should have a sufficiently high Radar Cross Section (RCS). Furthermore, at high frequency, miniaturization of tag elements complicates the fabrication feasibility which should also be evaluated.

Therefore, several designs have been reported in the literature to support these factors [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. In [10], without the use of a retro-reflector, three Dielectric Resonator (DR) linear arrays were arranged to allow coding of 3-bits (i.e. 8 tags) where ±35° retro-directivity is achieved. On the other hand, DR arrays of cylindrical and spherical shapes have been combined with dihedral reflector, trihedral reflector, Luneburg lens, and homogeneous lens [11], [12], [13], [14], [15], [16] and realized at different frequency ranges. Although DR-based retro-reflector provides good stability of ID over the operational angles, two main drawbacks are reported. First, the coding capacity is limited by the frequency separation between two consecutive modes. Therefore, for a specific resonance mode, the operational bandwidth within which we can codify is low in order to avoid the danger of misinterpretation with the next resonance mode. Second, DRs have a high relative permittivity which leads to small element sizes. As frequency increases, the realization of small elements of μm feature sizes becomes difficult, yet with a hardship of integration with a retro-reflector device.

Using a Frequency Selective Surface (FSS) as a coding structure has shown many drawbacks which are mainly the non-stability of tag ID over the operational angle [17], [18], [19]. In respective FSS designs, the angular response has been evaluated based on power consideration only where the RCS drops to 6 dB from its maximum without any consideration about the ability of the coded reflector to reflect its ID over all these incidence angles. ID stability over angle is an important practical limitation since, in case of the disappearance of ID or unidentifiable ID (for instance, due to a rippled response), this would simply deprive the tag of its main function (i.e. identification).

Photonic Crystal (PhC) resonators coupled to a dielectric waveguide have been also used as a coding structure in [20] and [21] with Luneburg lenses. Rod antennas were used to couple the energy from the lens focal area to 2-bit PhC resonator tags. Several PhC resonators were arranged around the lens periphery every 18° [20] or 15° [21]. Although the design can be realized at sub-terahertz frequencies, many drawbacks are seen. First, the coding capacity is limited to a few bits due to space limitation, where each rod antenna can couple the energy to a limited number of resonators. Second, the tag ID can be supported for only discrete angles where the rod antennas are integrated into the lens (multiple integers of 18° [20] or 15° [21]). Third, there is additional effort to design rod antennas as coupling elements between the lens and PhC resonators. A solution toward sparing the need of these rods is proposed in [22] by using quasi-conformal transformation optics to build a flattened lens. However, the lens has been tested with a metallic reflector instead of a coding particle.

In [23], we proposed a frequency-coded lens by a different coding structure than those reported in the literature which is a 1D PhC resonator. The coupling of a 1D PhC resonator with a homogeneous lens has been addressed where an increase in RCS by the square of the lens collimation gain was confirmed by measurements. However, the compatibility of a 1D PhC resonator with a lens has been found for an angle that relates to the axis between the resonator position behind the lens and the lens center. To address a wide-angle response, we extend the previous work by employing a curved 1D PhC resonator.
that covers a larger space around the lens. Contrary to other coding structures which employed discrete elements in the lens focal area, a curved 1D PhC resonator is a continuous structure that helps in maintaining the tag ID over the whole range without any discontinuity. In contrast, discrete coding elements cause some blind regions in the angle range where the tag can be identified. In other words, continuity in coding structure leads to continuity and stability in the tag ID over angles of operation. Another advantage related to coding capacity is that with a 1D PhC resonator the tag can be coded in the volume along the lens optical axis [24], instead of coding on the surface like in DR and FSS structures. This leads to a higher coding capacity compared to literature. Finally, the proposed solution in this paper can be easily fabricated at high mm-Wave or THz frequencies.

The paper is structured into six sections including this introduction section. In Section.II, we present the operation principle of the frequency-coded lens by a curved 1D PhC resonator including a design parametric study based on EM simulation. An analysis of the frequency coding of the proposed landmark is presented in Section.III. Section.IV describes the fabrication of the coded lens and presents the experimental validation. In Section.V, this work is compared to similar work in the literature. Finally, we close the paper with a summary.

II. RETRO-DIRECTIVE FREQUENCY CODED LENS

A Photonic Band Gap (PBG) where the light can be prohibited from propagating through a structure can be realized by the so-called photonic crystals. PhCs are periodic structures latticed with low- and high-index materials in one- (1D-), two- (2D-), or three- (3D-) dimensional configurations. The periodicity besides a sufficiently high index ratio can produce a PBG in the direction of propagation with a complete reflection in the backward direction similar to a mirror. A Bragg mirror is the simplest form of PhC where the low- and high-index materials are stacked in one dimension. To realize 1D PhC resonators, a defect layer should be inserted between two Bragg mirrors which act similar to a Fabry-Perot resonator. In Figure 2(a), a PhC resonator is designed by introducing a defect layer between two Bragg mirrors in the form of (LH)^2D(HL)^2 where L, H, and D stand for low-index, high-index, and defect layer. For our demonstration at mm-Wave frequency, a Bragg mirror is designed to provide a PBG in the frequency range (69 GHz-116 GHz) with a center frequency of 92.5 GHz [25]. A low index material of $\epsilon_{254} = 2.0$ and a high index material of $\epsilon_{L}^{H} = 10.2$ are selected for our investigation due to their availability with sufficiently low tangent loss. The symmetrical PBG is realized by selecting the layer thicknesses a quarter wavelength of the band gap center frequency inside the low and high index materials which are calculated as $d_{L} = 0.57$ mm and $d_{H} = 0.254$ mm, respectively. The resonator has a dimension of $L \times W$ and is excited by a plane wave whose direction of incidence is defined by the spherical coordinate $\theta_{inc}$ and $\phi_{inc}$. The resonator generates a notch at the resonance frequency in the backward direction and a peak in the forward direction.

The main parameters that control the resonance position are the defect layer thickness ($d_{def}$) and permittivity ($\epsilon_{r}^{def}$), while the quality factor of the resonance can be controlled by the layer stack and the number of layers; estimated formulas of defect resonance frequency can be found in [26]. Furthermore, figures and formulas showing the defect mode chart as a function of the optical thickness ($n_{def}d_{def}$) can be found in [27], where $n_{def}$ is the defect refractive index.

In our investigation, we choose a defect thickness of 1.37 mm with low permittivity of 2.0. Figure 3 presents the simulated RCS of a planar PhC resonator of square shape for two different lengths (28 mm and 56 mm). For the resonator of 28 mm length, the mono-static RCS for different angles of incidence (0° to 4° in a step of 2°) is plotted. For the 28 mm-length cases, when the resonator is excited by a plane wave in a normal incidence ($\phi_{inc} = 0^\circ$), a deep notch in the backscattered signal is observed at around 82.5 GHz which
represents the frequency code of our landmark. Outside the notch, a large scattering magnitude is observed which is comparable to the scattering of a metal plate of the same size, see Figure 3. Therefore, the resonator acts as a notch-filter at its resonance frequency and a good reflector (i.e. mirror) outside the resonance. When the resonator is interrogated by an incidence angle different from the normal excitation, the scattering magnitude outside the notch starts to degrade where the notch ID is kept for angle 2° and totally lost at 4°. This can be explained by the Snell’s law where most of the scattered power is re-directed to the specular direction and low RCS is observed in the retro-direction. Doubling the size of the resonator would increase the RCS by about 12 dB, compare the RCS of 28 mm-length and 56 mm-length in Figure 3, while the retro-directivity is kept low. Therefore, a square-shaped PhC resonator can be operated only when the reader interrogates the resonator by angles at or close to normal incidence.

In our system, as the reader may excite the tag under any angle of incidence, the planar design would not suit our application. A solution that may leap to minds is to structurally modify the resonator from planar to curved shape, as shown in Figure 2(b). However, even with changing the curvature radius, we find that the resonator properties changed since the incident divergent beam interacts with resonator parts differently which causes interference in the scattering response. Consequently, a rippled response is observed in the backscattering spectrum which overlays the notch.

A solution is to generate focused beams of high gain that can excite a semi-planar area of the curved resonator. Such beams should be flexibly steered through the PhC resonator curvature as the angle of incidence varies. This can be realized by locating the curved PhC resonator in the focal area of a spherical or cylindrical lens, as illustrated in Figure 4. The lens operates as a focusing device by collecting the incident wave across its aperture and concentrating it in a space behind its surface. A curved resonator in the lens focal area would be excited by a high-gain beam with a narrow beamwidth confined to a semi-planar area of the resonator. The resonator couples a portion of the incident power back to the interrogator through the lens again. At resonance, the resonator would still create a notch at which less energy is coupled to the lens. Outside the resonance, the resonator acts as a metallic cap similar to those discussed in [28]. Since the wave travels twice in the lens, in both the transmission and the reflection channels, the expected RCS level is proportional to the square of the lens gain. For different incidence directions, the lens is capable of focusing the beam to a focal area on the opposite side of the lens owing to its symmetry which should provide a wide-angle retro-directive response. In the coming sections, the RCS and resonance behavior of a curved 1D PhC resonator combined with a lens is compared to the case of a planar 1D PhC resonator as a reference structure.

A. LENS CHARACTERISTICS

In our investigations, we employed the homogeneous spherical type made of uniform material with a constant relative permittivity ($\epsilon_r$). The dependency of lens characteristics on lens parameters has been discussed in [29], [30], and [31]. In [23], it is found that the focal area of a spherical homogenous lens ($R_l = 20$ mm and $\epsilon_r = 2$) calculated at $f = 92.5$ GHz is located 4.4 mm from the lens periphery. The same lens is used here where the lens is excited alone by vertically z-polarized plane wave in order to characterize its focal area. In Figure 5, the normalized electric-field ($E_z$) is plotted in both E-plane ($xz$ plane) and H-plane ($xy$ plane) over an arc 4.4 mm behind the lens. The 3 dB-width in both planes is approximately the same of around 4.2°. At the same radius of 24.4 mm, this leads to a 3-dB focal spot area of about $\lambda^2/4$ in both planes at $f = 92.5$ GHz which is equivalent to 2.6 mm² calculated by the equation $\pi [x_t' \tan (\Theta_{3dB})]²$, where $x_t'$ represents the focal area position along the optical axis $x'$ and $\Theta_{3dB}$ represents

![FIGURE 3. Simulated mono-static RCS of planar squared-shaped 1D PhC resonator of different length: (1) 28 mm length that is simulated at different angle of incidence (ϕ_inc = 0°, 2°, and 4°) and (2) 56 mm length that is simulated at ϕ_inc = 0°, compared to the mono-static RCS of metal plates of the same size.](image-url)

![FIGURE 4. Cross-section of the combination of a curved PhC resonator with a spherical homogeneous lens. The curved PhC resonator has a height of W as represented in Figure 2(b). A cross-section of the biggest curved resonator has a semi-circular ring shape and completely covers a half circle around the lens with a = 180° and $\beta = 0°$. α and β represent the central angle and cut angle respectively. $R_l$ and $R_c$ are the lens radius and the location of the curved resonator measured from the lens center.](image-url)
the focal area 3-dB beam-width. Therefore, the curved PhC resonator should have a size greater than 2.6 mm² in the focal spot in order to be efficiently excited by the 3-dB power of the first main lobe of the beam. This can be only controllable by varying the curved PhC resonator height (W) indicated in Figure 2(b).

**B. CODED LENS BY CURVED PHOTOニック CRYSTAL RESONATOR**

Back to the combination of the lens with a curved PhC resonator depicted in Figure 4, the curved PhC resonator is designed to have a radius $R_c$ and is placed at the same radius around the lens. Full coverage of a circular half-plane around the lens can be achieved by a semi-circle ring shape of the resonator with a height (W), see also Figure 2(b). The resonator can be symmetrically clipped from both edges by the cut angle $\beta$ to create a shape that makes a central angle of $\alpha$. As a first guess of dimensions, we fixed the cut angle to $\beta = 40^\circ$, the resonator position to $R_c = 24.5$ mm, resonator height to $W = 11$ mm, and PhC resonator parameters to a defect thickness of 1.37 mm and layer arrangement of (LH)^2D(HL)^2.

To clarify the operation of our landmark, the electric field distribution in the central cross-sectional plane of the lens and the resonator is plotted for two incident angles at the notch frequency, Figure 6. We observe that the lens in both cases effectively focuses the plane wave to a region exactly opposite to the incoming wave behind the lens where the resonator is placed. An internal reflection is also observed by the rippled distribution inside the lens. This causes some reflections that superimpose the coming reflection from the resonator and appears in the RCS spectrum as ripples. Since these reflections occur early in time and do not interfere with reflections that come afterward which importantly carry the resonator ID, the early reflections can be time-gated out to produce a less rippled RCS spectrum. At notch frequency, a strong electric field concentration in the defect layer is observed for both angles. This indicates that the resonator traps some energy at its resonance frequency and couples less energy back to the lens which preserves the tag ID in the backscattering to the same direction of the interrogator.

For frequencies outside the notch, the lens acts as an efficient mirror that couples high energy to the lens contributing to a high RCS response. Referring to Figure 7, the mono-static RCS for both angles shows a high RCS outside the notch with a little variation over the angle. Contrariwise, a deep notch is seen with a slight deviation in the notch position and a noticeable difference in the notch depth. The difference in the notch behavior as the angle changes can be explained by Figure 6 where we observe some low energy spots that are located in the resonator defect around the main focal spot. As the angle of incidence changes, these spots encounter different medium of posture causing the change in notch depth and position.
In Figure 7, the mono-static RCS of a planar PhC resonator of square shape (28 mm length) is plotted for comparing the resonator characteristics with the case of a curved resonator combined with a lens. Originally, the planar PhC resonator resonates at a frequency of around 82.6 GHz. A noticeable shift in the resonance frequency is seen when the curved resonator is combined with the lens which can be attributed to a loading effect since the resonator is loaded by a lens with a permittivity of 2. In addition, the focal area hits a resonator with a semi-planar shape rather than a planar which seemingly reduces the optical thickness of the resonator causing a blue shift in the resonance. Also, it can be noted from Figure 7 that the mono-static RCS of the combination with a 20 mm radius lens has approximately the same RCS level in all cases whereas its maximum value is confined when the resonator is missed, leaving less RCS that is caused only by the reflection from the lens. For cut angle 80° (Figure 8(d)), we approach the case where roughly a planar PhC resonator is located in the focal area. Therefore, the tag can be only identified within a narrow range of angles (\(\phi = 0^\circ\) to 10°), but still with a better performance with respect to the identification angle compared to a planar resonator. Figure 9 shows the simulated RCS results when the resonator height (W) varies from 5 mm to 15 mm in a step of 1 mm and the incident plane wave is fixed for all cases (\(\theta = 90^\circ\) and \(\phi = 0^\circ\)). The notch frequency appears almost in all cases whereas its maximum value is confined when the height varies between the 9 mm and 11 mm. The effect of varying the layer arrangement around the defect layers for a finite-size PhC resonator on notch characteristics has been studied in [32]. It is found that increasing the number of layers around the defect improves the notch quality factor but also degrades the notch depth. In this paper, varying resonator characteristics with the case of a curved resonator combined with a lens. It is worth mentioning that the appearance of the notch is seen for a wide range of angles, where 170° can be covered. Furthermore, as the incidence angle changes the notch remains undistorted when compared to existing

![Figure 8](image-url) Simulated RCS results by varying the incident plane wave angles in azimuth plane (\(\phi\)) for different cut angles, (a) \(\beta = 0^\circ\), (b) \(\beta = 20^\circ\), (c) \(\beta = 40^\circ\), and (d) \(\beta = 80^\circ\).
works in the literature in which either the ID is astable over all angles [17], [18], [19], stable for only discrete angles [20], [21], or stable over narrower angular range like in [9], [10], [11], [13], [14], [15], and [16]. This is because all previous work that uses a lens as a retro-reflective device, replies by placing discrete coding particles in the focal region causing discontinues in the spectrum and missing the ID for angles in-between elements. In contrast, in this work, a curved PhC resonator, which is a symmetric and of a continuous structure, can provide approximately the same channel over wide-angle ranges.

III. FREQUENCY CODING OF LANDMARKS

The coding particle in our combination is the curved PhC resonator where different defect thicknesses or permittivities provide one or multiple notches with different spectral positions. The reader can easily identify the tag by detecting the number of notches and their positions in a specified number of information channels \(N\). Information channels are determined by the reader bandwidth \(BW_r\), reader resolution \(\Delta f\), and the notch bandwidth \(BW_n\) where \(N = \text{min}(\Delta f, BW_r)/BW_n\). Higher resolution allows the reader to discriminate between two codes with a low spectral spacing between their notches. On the other hand, lower notch bandwidth allows codifying more bits in the specified bandwidth. Interestingly, unlike other coding structures in the literature, the 1D PhC resonator can be frequency-coded in the volume rather than the surface of the tag. Since the axis of coding is along the lens optical axis, this allows the creation of multiple notches rather than one notch in the spectrum. The coding can be performed by varying the number of defects \(K\) in order to produce a frequency code defined by the presence or absence of a notch in the pre-defined information channels. For each \(K\), different sets of codes can be produced, therefore, the total coding capacity in bits can be calculated by summing the codes for each \(K\) as follows: \(C = \sum KC(K)\). In this section, the frequency coding of the combination is analyzed by considering one and two defect modes \((K = 1, 2)\), however, the analysis can be extended for larger \(K\).

A. SINGLE DEFECT LAYER \((K = 1)\)

In our investigations, the reader operates in the W-band \((75 \text{ GHz} - 110 \text{ GHz})\) which is covered by our design of the PBG, see section II. Assuming the crystal lattice of \((\text{LH})^2\text{D(\text{HL})}^2\), the notch resonance has about 4.5 GHz of bandwidth \(BW_n\) which provides 7 frequency codes \((C(1))\), each has a unique position. In Figure 10(a), the spectral signature of five codes is shown in the band 75 GHz to 95 GHz with their respective defect layer thickness.

In principle, a single resonance is not uniquely coded with a specified defect thickness, whereas different defect thicknesses can produce the same resonance frequency. This can be illustrated by plotting the mode chart of a single defect layer as a function of the defect thickness, shown in Figure 10(b). When the defect thickness is equal to 0, the resonator has a lattice \(\text{LHLH}^2\text{LHL}\) where two high-index layers stacked together would produce a defect layer that resonates at the central frequency of PBG. Increasing the defect thickness yields a decrease in the frequency. A further increase higher than 0.2 mm puts the resonator in the mirror region where no resonances are produced, up to a thickness of 0.9 mm. Beyond 0.9 mm, the resonance frequency drops up to about 1.7 mm to enter the second mirror region. The resonance starts to appear again when the thickness is greater than 1.8 mm with the same decaying effect in the resonance position. When the defect thickness reaches 2.8 mm, notch pairs start to emerge in the PBG whose spectral spacing is proportional to the defect thickness. As the defect thickness increases, higher order modes are excited which generates...
multiple notches to exist in the PBG. Although the mode chart is not an injective function; this is useful in finding the optimized defect layer for a specific frequency that provides the best notch characteristics; low bandwidth and high depth.

The coding results of the combination are compared to the Transfer Matrix Method (TMM) simulator, e.g. [33], which assumes an infinite size of the resonator without a lens and reflects the reference value of the notch position. A slight blue shift in the resonance position is observed with a maximum of about 4 GHz. The shift is caused by loading the curved PhC resonator by a lens, in addition to the curved shape of the resonator that alters the optical length.

**B. DUAL DEFECT LAYER (K = 2)**

Two methods to introduce two notches in the spectrum are either (1) by using one defect layer and increasing its thickness in order to excite dual mode, or (2) by using two defect layers located at a different position in the resonator structure. Back to Figure 10(c), employing the first method, a notch pair can be obtained with a defect layer of 2.8 mm and beyond seen by a notch pair in the mode chart. However, it is found that these modes are less coupled to the lens and provide deficient notches in the backscattering.

Using the second method, better performance is achieved where two defect layers having the same thickness are installed in the resonator structure creating the lattice HLD(1)LDH(2)LHD, where D(1) and D(2) are the first and second defect layers respectively, see Figure 11(a). Figure 11(b) shows the mono-static RCS spectrum of three frequency codes where each code has at least one unique notch position. Notably, an equal layer thickness for both defects gives the largest depth for both notches. The mode chart of the combination, shown in Figure 11(c), exhibits similar behavior to the TMM simulation where two notches are seen at the corresponding defect thickness except for a slight shift in their positions. As previously mentioned, the resonator acts as a mirror in the regions where no resonances exist in the chart. Considering the same notch bandwidth, we can add 7 frequency codes to those calculated for the single layer cases. Additional frequency codes can be obtained by extending the resonator to have multiple defect layers (K ≥ 3 ) in order to generate more than two notches in the spectrum.

**IV. RESONATORS FABRICATION AND EXPERIMENTAL RESULTS**

In this section, two frequency-coded lenses with single- and dual-defect PhC resonators are fabricated and experimentally examined.

**A. FABRICATION PROCESS**

Three main components were manufactured separately to compose and realize the designed landmark: the curved PhC resonator, the spherical dielectric lens, and the support structure. Figure 12(a) and Figure 12(b) present the fabricated single and dual-defect landmarks, respectively.

Low-index layers, as well as defect layers, were built as parts portions of half-cylindrical shells of 11 mm height with different radii that define their locations in the curved resonator and also their location from the lens surface. These layers were 3D printed from Cyclic Olefin Copolymer (COC) material with \( n_L = \sqrt{2} \). The thickness of the defect layers for the single defect and dual defect resonators has been chosen to be 1.55 mm and 1.2 mm, respectively, while low-index material layers were selected to be 0.57 mm thick. High-index material layers were obtained by etching a PTFE ceramic substrate (RT/duroid 6010.2LM) with \( n_H = \sqrt{10.2} \) and then...
FIGURE 12. Picture of two fabricated landmarks showing a homogenous lens made of COC material combined with (a) Single defect PhC resonator (HLHDLHL) and (b) Dual defect PhC resonator (HLHDLHLHDLHLH). Layer D, D(1), and D(2) have a thickness of 1.55 mm, 1.2 mm, and 1.2 mm, respectively.

creating planar sheets of 11 mm width. Taking advantage of the ceramic material plasticity, the high-index layers were easily inserted between the stiff COC layers. All the layers were then manually stacked without employing any extra adhesive material to form the curved PhC resonator. The focusing spherical dielectric lens was 3D printed of the same COC material with a lens radius of \( R_l = 20 \text{ mm} \). Curved resonators have been trimmed with a cut angle of 30° and 40° for the single defect and dual defect resonators respectively, see Figure 12.

To ensure the PhC resonator alignment in the focal area of the lens, in addition to a well-established placement of the PhC’s layers as well as minimizing the air gaps between them, a dedicated support structure was designed consisting of a uniform combination of the landmark components. The support structure was 3D printed with a low infill density so that 90% of the structure is filled with air and only 10% was COC material. This guarantees a minimum effect of this structure on the resonator’s behavior.

B. MEASUREMENT PROCEDURE
The measurement setup is exhibited in Figure 13. A vector network analyzer (VNA) based system was employed as an interrogator where the ZC110 frequency conversion module extends the RF signal of the ZVA67 VNA with a multiplication factor of 8 to operate at a frequency range between 75 GHz and 110 GHz as a transceiver TRX. A 26 dBi horn antenna was attached to the flange of the extender’s WR-10 rectangular waveguide. To verify the angular detection performance of the landmarks, a motorized turntable, which rotates in an azimuth plane with a 2° angular step size was implemented. The landmark was fixed on a Styrofoam block on top of the rotation table to maintain alignment with the interrogator’s horn antenna at a distance \( d \approx 1.25 \text{ m} \). Landmarks were placed in a way that the center of the lens is directly located at the rotation pivot of the turntable.

A control PC with a running MATLAB script directed the measurement procedure (sent control commands to the

FIGURE 13. Measurement setup showing the fabricated coded lenses placed on a rotary table, a distance of around 1.25 m in front of a 26 − dB gain horn antenna connected to a VNA for measuring the S11 coefficients as a function of angle of rotation.

FIGURE 14. Measured mono-static RCS spectrum for two frequency coded lenses coded by: (a) a single defect PhC resonator (defect thickness = 1.55 mm) and (b) a dual defect PhC resonator (equal defects thicknesses = 1.2 mm).
FIGURE 15. RCS spectrums plotted for a wide range of incidence angles for four cases: (a) Single defect PhC resonator (measured), (b) Single defect PhC resonator (simulated), (c) Dual defect PhC resonator (measured), and (d) Dual defect PhC resonator (simulated). Angle step sizes were taken at 2.5° and 2° for the simulated and measured results respectively. Boundaries have been plotted to highlight the notch. In (a) and (b), the boundary was chosen to be −13 dB and −8 dB respectively, at around 80 GHz. The boundary was plotted at −13 dB (solid line) and −9 dB (dotted line) in (c) for the first and the second frequency, at around 94 GHz and 102 GHz, respectively, and −10 dB around both frequencies in (d). Simulated results were plotted for positive angles only because of symmetry.

In Figure 15, mono-static spectral signatures are plotted for the coded lens by single and dual defect resonators for angles of incidence in the range −40° to 40° and −30° to 30°, respectively. Measurements are compared to the EM simulated results plotted for only positive angles because of symmetry. In all plots, a notch line is characterized by a low RCS ($\text{RCS}(f, \phi_{\text{inc}}) \leq \chi$) where $\chi$ define the notch line boundaries, see values of $\chi$ in Figure 15. The notch line clarifies the notch characteristics where line intensity denotes the notch depth and the line width is proportional to notch bandwidth. In a single defect resonator case, a deep notch at about 80 GHz appears in both simulation and measurements and covers a wide-angle range of 80°. A better notch characteristic of more depth and less bandwidth is observed in the measured results. A slight variation in the notch position is observed in the measured results. This is explained by some variation in the curved crystal lattice along the focal line where layers have been stacked manually and small gaps between them can cause a shift in defect mode resonance. For the dual defect resonator, two notches are observed at around 96 GHz and 102 GHz with slight deviations between measurement and simulation subjected to errors in fabrication. However, both results indicate conservancy of notch characteristics over a wide angle of 60°.

V. COMPARISON WITH SIMILAR WORK

Table 1 shows the comparison between related designs in the literature and this work. Due to the possibility of coding bits in the volume of the resonator, this landmark has
TABLE 1. Selected coded retro-reflectors compared to this work. (x) indicates that the corresponding result has not been evaluated or is not evaluable. Coding capacity is the calculated value. Angular responses are the angle range at which the RCS reduces 6 dB from its maximum. The ID stability over the operational angle measures whether the tag can be identified by its ID over the whole range.

| Reference | Retro-directive reflector | Coding particle | Coding Capacity | Angular response | ID stability over operational angle | Frequency |
|-----------|---------------------------|-----------------|----------------|------------------|-------------------------------------|-----------|
| [10]      | Without retro-reflector   | DR array        | 3 bits         | ±35°             | Stable                              | 100 GHz   |
| [11], [12]| Homogeneous lens Luneburg lens | Cylindrical DR       | 2.52 bits      | ±50°             | Stable                              | 10 GHz    |
| [13]      | Dihedral corner reflector | Cylindrical DR placed on corner reflector plates | 2.32 bits | ±20°             | Stable                              | 7 GHz     |
| [14], [15]| Dihedral corner reflector | Spherical DR | 5.5 bits       | ±20°             | Stable                              | 64 GHz, 73 GHz, 86 GHz, 100 GHz, 230 GHz |
| [9], [16] | Trihedral corner reflector | Spherical DR | 2 bits         | ±20°             | Stable                              | 84 GHz, 100 GHz |
| [17]      | Homogeneous spherical lens | Cross-dipole FSS | 3.2 bits       | ±60°             | Not Stable                          | 82 GHz    |
| [18]      | Trihedral corner reflector | Cross-dipole FSS | 3 or 5 bits   | ±22°             | Not Stable                          | 77 GHz    |
| [19]      | Trihedral corner reflector | Gridded Square-Ring FSS | 5.5 bits   | ±35°             | Not Stable                          | 77 GHz    |
| [20]      | Spherical Luneburg lens   | PhC resonators coupled to dielectric waveguide | 2 bits     | Discrete angles at multiple of 18° over ±36° | Stable for only discrete set of angles where the resonators are coupled to the lens | 240 GHz |
| [21]      | Planar Luneburg lens      | PhC resonators coupled to dielectric waveguide | 2 bits     | Discrete angles at multiple of 15° over ±65° | Stable for only discrete set of angles where the resonators are coupled to the lens | 80 GHz    |
| [22]      | Flattened Luneburg lens   | Metallic (No coding element) | x               | ±37° or ±50°     | No coding element                  | 40 GHz    |

This work | Homogeneous lens | Curved 1D PhC resonator | 3.8 bits | Simulated ±85° \(\pm 40°\) for single resonance \(\pm 30°\) for two resonances | Stable | W-band |

the potential to provide high coding capacity. In this paper, we demonstrate single- and dual-defect resonators where each can provide 7 code combinations leading to 3.8 bits. Our proposed design can provide a high retro-directivity caused by the continuity of the 1D PhC resonator along the lens focal line. The simulated retro-directivity is the highest among reported works which can reach ±85° by completely covering the focal area with a curved PhC resonator. We show by measurements a retro-directivity of 80° and 60° for single- and dual-defect resonators. Additionally, codes represented by a notch or notches in the RCS spectrum are stable and appear for all operational angles. This landmark is realized at the W-band which solves the difficulty of fabricating coding elements like DRs at those frequencies. In summary, our landmark gives the best code stability over a wide operational angle.

VI. CONCLUSION

In this paper, a wide-angle frequency-coded lens by a curved PhC resonator is proposed. Curved PhC resonators are placed in the focal line of a homogenous lens of low permittivity.

Due to the continuity of curved PhC resonators along the lens focal and the possibility of volume-coding along the lens optical axis, outstanding performance is achieved, surpassing existing coded retro-reflectors. Continuity allows a wide-angle retro-directivity where a high RCS spectrum that carries a deep notch is recognized for all angles. This is unlike coded lenses in the literature that offer a detected code for only discrete angles due to the discrete placement of coding structures in the lens focus.

On the other hand, volume-coding permits the integration of multiple defects that gives multiple notches in the spectrum, which significantly improves the coding capacity. In the state-of-the-art landmarks, no possible employment of different resonators for creating multiple peaks or notches in the spectrum. Although coding by two peaks were demonstrated in [20], the codes lose their characteristics for wide interrogation angles.

In a demonstrator design for the W-band, two coded lenses with single defect and dual defect resonators are fabricated and tested. Measured results demonstrate a reliable detection of single notch codes and dual notch codes over a wide
angle of 80° and 60°, respectively. In all our investigations, a TE-polarized wave is used, however, a similar performance can be obtained for TM polarization where the structure is found to be nearly polarization independent.

REFERENCES

[1] H. Liu, H. Darabi, P. Banerjee, and J. Liu, “Survey of wireless indoor positioning techniques and systems,” IEEE Trans. Syst., Man, Cybern. C. Appl. Rev., vol. 37, no. 6, pp. 1067–1080, Nov. 2007.
[2] G. Mendoza-Silva, J. Torres-Sospedra, and J. Huerta, “A meta-review of indoor positioning systems,” Sensors, vol. 19, no. 20, p. 4507, 2019.
[3] S. Preradovic and N. C. Karmakar, “Chipless RFID: Bar code of the future,” IEEE Microw. Mag., vol. 11, no. 7, pp. 87–97, Dec. 2010.
[4] R. Das, Chipless RFID—The End Game. Cambridge, U.K.: IDTechEx, Feb. 2006. [Online]. Available: https://www.idtechex.com/en/research-article/chipless-rfid-the-end-game/435
[5] M. El-Albi, A. A.-H. Abbas, A. Abuelhaija, F. Zheng, K. Solbach, and T. Kaiser, “High-accuracy indoor localization based on chipless RFID systems at THz band,” IEEE Access, vol. 6, pp. 54355–54368, 2018.
[6] M. El-Albi, A. A.-H. Abbas, A. Abuelhaija, K. Solbach, and T. Kaiser, “Chipless RFID infrastructure based self-localization: Testbed evaluation,” IEEE Trans. Veh. Technol., vol. 69, no. 7, pp. 7751–7761, Jul. 2020.
[7] H.-J. Song and T. Nagatsuma, “Present and future of terahertz communications,” IEEE Trans. THz Sci. Technol., vol. 1, no. 1, pp. 256–263, Sep. 2011.
[8] M. El-Albi, A. A.-H. Abbas, and T. Kaiser, “Chipless RFID tags placement optimization as infrastructure for maximal localization coverage,” IEEE J. Radio Freq. Identif., vol. 6, pp. 368–380, 2022.
[9] A. A. Abbas, M. El-Albi, A. Abuelhaija, K. Solbach, and T. Kaiser, “THz passive RFID tag based on dielectric resonator linear array,” in Proc. 2nd Int. Workshop Mobile THz Syst. (IWMTS), Bad Neuenahr, Germany, Jul. 2019, p. 1–5.
[10] A. A. Abbas, M. El-Albi, A. Abuelhaija, K. Solbach, and T. Kaiser, “Wide-angle RCS enhanced tag based on dielectric resonator–lens combination,” Frequenz, vol. 74, no. 1–2, pp. 1–8, Jan. 2020.
[11] A. A. Abbas, “Dielectric resonator-based passive chipless tags for identification and ranging,” Ph.D. dissertation, Inst. Digit. Signal Process., Univ. Duisburg-Essen, Germany, Oct. 2020.
[12] A. A. Abbas, M. El-Albi, A. Abuelhaija, K. Solbach, and T. Kaiser, “Corner reflector tag with RCS frequency coding by dielectric resonators,” IET Microw., Antennas Propag., vol. 15, no. 6, pp. 560–570, Mar. 2021.
[13] K. Solbach, A. A. Abbas, M. El-Albi, A. Abuelhaija, and T. Kaiser, “Experimental demonstration of double-notch RCS spectral signature of corner reflector tag for THz self-localization system,” in Proc. 3rd Int. Workshop Mobile THz Syst. (IWMTS), Essen, Germany, Jul. 2020, pp. 1–4.
[14] A. A. Abbas, M. El-Albi, A. Abuelhaija, K. Solbach, and T. Kaiser, “Metallic reflectors with notched RCS spectral signature using dielectric resonators,” Electron. Lett., vol. 56, no. 6, pp. 273–276, Mar. 2020.
[15] A. Jiménez-Sáez, A. Alhaj-Abbas, M. Schüßler, A. Abuelhaija, M. A. Kaliteevski, M. Schusler, M. Sakaki, L. Samfall, N. Benson, M. Hoffmann, R. Jakoby, T. Kaiser, and K. Solbach, “Frequency-coded mm-wave tags for self-localization system using dielectric resonators,” J. Inf. Millim., THz Waves, vol. 41, no. 8, pp. 908–925, Aug. 2020.
[16] J. Sanchez-Pastor, A. Jimenez-Saez, M. Schuessler, and R. Jakoby, “Frequency-coded spherical retroreflector for wide-angle indoor localization tag landmarks,” in Proc. 4th Int. Workshop Mobile THz Syst. (IWMTS), Jul. 2021, pp. 1–5.
[17] A. Jimenez-Saez, M. Schuesler, M. El-Abi, A. A. Abbas, K. Solbach, T. Kaiser, and R. Jakoby, “Frequency selective surface coded retroreflectors for chipless indoor localization tag landmarks,” IEEE Antennas Wireless Propag. Lett., vol. 19, no. 5, pp. 726–730, May 2020.
[18] J. Sanchez-Pastor, A. Jimenez-Saez, M. Schuesler, and R. Jakoby, “Gridded square-ring frequency selective surface for angular-stable response on chipless indoor localization tag landmarks,” in Proc. 15th Eur. Conf. Antennas Propag. (EuCAP), Mar. 2021, pp. 1–5.

P. Kadera, A. Jimenez-Saez, T. Burmeister, J. Lacić, M. Schusbler, and R. Jakoby, “Gradient-index-based frequency-coded retroreflective lenses for mm-wave indoor localization,” IEEE Access, vol. 8, pp. 212765–212775, 2020.

P. Kadera, J. Sanchez-Pastor, L. Schmitt, M. Schuelller, R. Jakoby, M. Hoffmann, A. Jimenez-Saez, and J. Lacić, “Sub-THz Luneburg lens enabled wide-angle frequency-coded identification tag for passive indoor self-localization,” Int. J. Microw. Wireless Technol., pp. 1–15, May 2022, doi: 10.1109/175908722000054X.

P. Kadera, J. Sanchez-Pastor, H. Eskandari, T. Tyc, M. Sakaki, M. Schusler, R. Jakoby, N. Benson, A. Jimenez-Saez, and J. Lacić, “Wide-angle ceramic retroreflective Luneburg lens based on quasi-conformal transformation optics for mm-wave indoor localization,” IEEE Access, vol. 10, pp. 41097–41111, 2022.

A. A. Abbas, Y. Zantah, K. Solbach, and T. Kaiser, “Frequency-coded lens by photonic crystal resonator for mm-wave chipless RFID applications,” in Proc. 4th Int. Workshop Mobile THz Syst. (IWMTS), Jul. 2021, pp. 1–5.

M. Bernier, F. Garet, E. Perret, L. Duvillaret, and S. Tédirj, “Terahertz encoding approach for secured chipless radio frequency identification,” Appl. Opt., vol. 50, no. 23, pp. 4648–4655, 2011.

C.-J. Wu and Z.-H. Wang, “Properties of defect modes in one-dimensional photonic crystals,” Prog. Electromagn. Res., vol. 103, pp. 169–184, 2010.

G. Panzarini, L. C. Andreani, A. Armitage, D. Baxter, M. S. Skolnick, V. N. Astratov, J. S. Roberts, A. V. Kavokin, M. R. Vladimirnova, and M. A. Kaliteevski, “Cavity-polarization dispersion and polarization splitting in single and coupled semiconductor microcavities,” Phys. Solid State, vol. 41, no. 8, pp. 1223–1238, Aug. 1999.

H. Neme, L. Duvillaret, F. Quesnel, and P. Kuzel, “Defect modes caused by twinning in one-dimensional photonic crystals,” JOSA B, vol. 21, no. 3, pp. 548–553, 2014.

J. R. Sanford, “Analysis of spherical radar cross-section enhancers,” IEEE Trans. Microw. Theory Techn., vol. 43, no. 6, pp. 1400–1403, Jun. 1995.

J. Thornton and K. Huang, Modern Lens Antennas for Communications Engineering, vol. 39. Hoboken, NJ, USA: Wiley, 2013.

G. Bekefi and G. W. Farnell, “A homogeneous dielectric sphere as a microwave lens,” Can. J. Phys., vol. 34, no. 8, pp. 790–803, Aug. 1956.

B. Schoenlinner, X. Wu, J. P. Ebling, G. V. Eleftheriades, and G. M. Rebeiz, “Wide-scan spherical-lens antennas for automotive radars,” IEEE Trans. Microw. Theory Techn., vol. 50, no. 9, pp. 2166–2175, Sep. 2002.

A. A. Abbas, Y. Zantah, and T. Kaiser, “On scattering of finite-size and finite-volume one-dimensional photonic crystal resonator for THz identification,” in Proc. 5th Int. Workshop Mobile THz Syst. (IWMTS), Jul. 2022, pp. 1–5.

M. Born and E. Wolf, Principles of Optics, 6th ed. New York, NY, USA: Pergamon Press, 1980.

A. AIJHA ABBAS received the B.Sc. degree in electrical/communication engineering from Yarmouk University, Irbid, Jordan, in 2010, the M.Sc. degree in electrical/communication engineering from the University of Jordan, Amman, Jordan, in 2016, and the Ph.D. degree from the University of Duisburg-Essen, Duisburg, Germany, in 2020. From March 2011 to July 2017, he worked as a Teaching Assistant and a Lecturer at Applied Science University, Jordan. He is currently working as a Postdoctoral Researcher with the Institute of Digital Signal Processing (DSP), University of Duisburg-Essen. His current research interests include antennas, photonic crystal, terahertz identification, UWB antennas, and chipless RFID tags.
YAMEN ZANTAH (Graduate Student Member, IEEE) received the B.Sc. degree in electronics and communication engineering from Al-Baath University, Syria, in 2011, and the M.Sc. degree in embedded systems engineering from the University of Duisburg-Essen, in 2019, where he is currently pursuing the Ph.D. degree with the Institute of Digital Signal Processing. From 2012 to 2014, he was the Head of the Communication Team, SADCOP, Syria. He is currently working as a Research Assistant with the Institute of Digital Signal Processing, University of Duisburg-Essen, where he is involved in multiple research projects. His current research interests include massive MIMO, terahertz (THz) beamforming and steering technologies, THz identification, channel sounding measurement systems, and modeling for mm- and THz waves. He has been in the organizing committee of the IEEE International Workshop Series on Mobile Terahertz Systems, since 2019.

ASHRAF ABUELHAIJA received the B.Sc. degree in communications and electronics engineering from Applied Science Private University, Amman, Jordan, in 2007, and the master’s and Ph.D. degrees in electrical engineering from the University of Duisburg-Essen, in 2010 and 2016, respectively. From 2012 to 2014, he was a Research Assistant at the Erwin L. Hahn Institute for Magnetic Resonance Imaging, Essen. From 2014 to 2016, he was a Research Assistant at the Department of Microwave and RF technology, University of Duisburg-Essen. He is currently an Associate Professor with the Department of Electrical Engineering, Applied Science Private University. His research interests include antennas and RF technology.

THOMAS KAISER (Senior Member, IEEE) received the Diploma degree in electrical engineering from Ruhr-University Bochum, Bochum, Germany, in 1991, and the Ph.D. (Hons.) and German Habilitation degrees in electrical engineering from Gerhard Mercator University, Duisburg, Germany, in 1995 and 2000, respectively. From 1995 to 1996, he spent a research leave with the University of Southern California, Los Angeles, CA, USA, which was grant-aided by the German Academic Exchange Service. From April 2000 to March 2001, he was the Head of the Department of Communication Systems, Gerhard Mercator University, and from April 2001 to March 2002, he was the Head of the Department of Wireless Chips and Systems, Fraunhofer Institute for Microelectronic Circuits and Systems, Duisburg. From April 2002 to July 2006, he was the Co-Leader of the Smart Antenna Research Team, University of Duisburg-Essen, Duisburg. In Summer 2005, he joined the Smart Antenna Research Group, Stanford University, Stanford, CA, USA. In Winter 2007, he joined the Department of Electrical Engineering, Princeton University, Princeton, NJ, USA, as a Visiting Professor. From 2006 to 2011, he headed the Institute of Communication Technology, Leibniz University of Hannover, Germany. Currently, he heads the Institute of Digital Signal Processing, University of Duisburg-Essen. He is the Founder and CEO of ID4us GmbH, an RFID centric company. He is the author and coauthor of more than 300 papers in international journals and conference proceedings and two books titled *Ultra Wideband Systems with MIMO* (Wiley, 2010) and *Digital Signal Processing for RFID* (Wiley, 2015). He is the Speaker of the Collaborative Research Center “Mobile Material Characterization and Localization by Electromagnetic Sensing” (MARIE). He was the Founding Editor-in-Chief of the *Electronics Letters* of the IEEE Signal Processing Society and the General Chair of the IEEE International Conference on UltraWideBand, in 2008, the International Conference on Cognitive Radio Oriented Wireless Networks and Communications, in 2009, the IEEE Workshop on Cellular Cognitive Systems, in 2014, and the IEEE Workshop on Mobile THz Systems, in 2018.