Wide Field of View Retrodirective Millimeter Wave Antenna Array With Pulse Modulation and Orthogonal Polarization States

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ABSTRACT This work presents novel techniques to realize a retrodirective millimeter wave antenna array with wide field of view. High gain arrays in phase conjugate configuration are used in combination with orthogonal polarization states and a novel pulse modulation technique to improve backscattering which finds its application in localization and enabling data transmission from sensor nodes. The proposed approach avoids the use of amplifiers thereby reducing the cost, complexity and power consumption of sensor nodes while providing a wide field of view. The basic building blocks of the proposed antenna array are compact one-dimensional (1D) slot arrays that can be designed with orthogonal linear polarizations. Their compact size limits the grating lobes under $-10$ dB level with respect to the main beam to enable $120^\circ$ retroreflective field of view, thus, eliminating the reflections in undesired directions while providing $90^\circ$ rotated linear polarization for the reflected signal with respect to the incident signal polarization. The orthogonal polarization states and compact size are achieved by using a two-layer structure and exploiting the characteristics of substrate integrated waveguide and rectangular cavities. Arrays are designed, prototyped and characterized to validate the proposed concepts.

INDEX TERMS Orthogonal polarization states, wide field of view, slot arrays, retroreflection.

I. INTRODUCTION

An amplifier-less backscattering retrodirective tag finds its application in several low power radio frequency (RF) systems such as sensors to sense displacement [1] and humidity in confined environment [2], data communication nodes [3], [4], as target in automotive radar [5] and millimeter wave imaging [6].

An active tag operating in the 76-81 GHz band is presented in [5]. In this work a low-noise amplifier is used in the tag to provide about 20 dB gain for the reflected signal. However, the active components increase the cost and complexity of the proposed tag. Similarly, an active antenna is proposed in [7] for inter-satellite data transmission. On the other hand, some passive tags rely on arrays in phase conjugate configuration (also known as Van-Atta arrays [8]) to increase the backscattered signal strength by reflecting the signal predominately in the direction of incidence. This property is known as retroreflection.

Several passive tags appear in the literature. In [9], a grounded coplanar waveguide patch antenna is used to realize a Van-Atta array for a single linear polarization at 26 GHz. The distance between the centers of the adjacent radiating elements is $0.8\lambda$. In [10], slots in a substrate integrated waveguide (SIW) are used to realize retrodirective arrays at 30 GHz for a single linear polarization. The inter-element spacing for these arrays is $0.7\lambda$. Microstrip patch antennas operating at 77 GHz with minimum inter-element distance of $0.77\lambda$ are used in [11] to realize a single linear polarization retroreflector designed to enhance the radar cross-section (RCS) of humans and other low profile objects. A circularly polarized retroreflector is presented in [12] with inter-element distance of $0.75\lambda$ at 25.45 GHz. Another RFID tag composed of two circularly polarized radiators connected with a filter coupled transmission line in presented in [13]. The filters are designed to realize a specific frequency response of the tag when it is illuminated by a reader signal. To our knowledge, all the passive tags previously proposed in the literature have large inter-element spacing, limiting the retroreflective FoV by raising the grating lobes after a few degrees displacement.
from broadside. As the Van-Atta arrays are essentially phased arrays, this large inter-element distance is expected to raise the grating lobes after a few degrees scan (theoretically ±8° of scan will result in grating lobes above −10 dB relative to the main beam for inter-element spacing of 0.8λ) and cause signal scattering in unwanted directions. These reflections will not only lower the backscattered signal strength of the retroreflector but also cause interference for nearby systems.

To enhance the target contrast with respect to the background clutter, a few passive tags with different incident and reflected signal polarizations were also reported. An orthogonally polarized retroreflector operating in Kυ band is presented in [14]. This RFID tag uses dual-polarized patch antennas operating at 30 GHz. The patch antennas and their feeding network are forcing a large spacing between the retroreflector array elements, causing grating lobes as mentioned earlier. In [15], wideband radiating elements are arranged in Van-Atta array configuration to provide orthogonal polarization states between the incident and reflected signals in W-band. The inter-element spacing is 0.79λ at 79 GHz. Beamforming is not possible in the plane perpendicular to the retroreflective plane due to the structure of the radiating elements used in this work. An L-band polarization rotating reflector with inter-element spacing of 0.7λ for airborne polarimetric synthetic aperture radar calibration is described in [16]. In addition to orthogonal polarization states, phase modulation is implemented in [17]. The proposed tag operates in X-band with inter-element spacing of 1.5λG with phase modulation realized by switching between different length transmission lines using PIN diode.

All above described tags have limited array FoV free of grating lobes. Those features are critical to increase the sensor detection sensitivity. This work presents techniques to provide strong reflection in the W band, with orthogonal polarization for a wide FoV, free of grating lobes. This is achieved with a compact radiating element in high gain arrays to reduce the tag’s cost and complexity. The W band has several advantages over K and Ka bands used in previous work. Firstly, the available bandwidth is broad (e.g. 4 GHz for automotive radar applications). Secondly, the antennas are more compact, assuming a given beamwidth. Of course, path loss is increased and this should be compensated with better antennas, having narrower beams and no grating lobes. The compact radiating element used in this tag allows two-dimensional (2D) array formation to enhance the array gain. This gain compensates the gain achieved by the active components presented in [5]. Furthermore, the inter-element spacing of the proposed tag in retroreflection plane is 0.48λ at 78.5 GHz which enables a 120° retroreflection FoV without raising the grating lobes above −10 dB for small arrays. Additionally, the incident and reflected signals have orthogonal linear polarizations for the proposed tag to increase the target contrast with respect to the background clutter. State-of-the-art W-band retroreflectors with polarization rotation available in the open literature have inter-element spacings of approximately 0.7λ. The inter-element spacing of 0.48λ achievable using the proposed technique is a significant improvement in FoV of Van-Atta array-based retroreflector. Finally, a modulation technique of the retransmitted signal is also incorporated in the tag to extend its functionality by enabling data transmission from the target.

The tag concept and design is presented in Section II. It is followed by discussions about the prototype fabrication and measurements in Section III. Finally, Section IV concludes this article.

II. CONCEPT AND DESIGN
A. RF SYSTEM WITH THE PROPOSED RETRODIRECTIVE TAG

Fig. 1 illustrates the use of the tag concept we are proposing in this article. The RF node comprises a retrodirective millimeter wave antenna array which reflects the incoming RF signal from the sink (a mobile reader or a fixed node) with a retrodirective reflection having maximum antenna gain at the same angle as the incoming signal. The retrodirective reflection increases the received signal strength at the sink and thus enhances the system range. It is also critical to have a wide retrodirective field of view where large reflected antenna gain is maintained to obtain the largest possible angular detection range. Since the antenna has no grating lobes over a wide FoV, interference signals from non-retrodirective directions are reduced. Further, the retrodirective antenna array rotates the incoming signal polarization. This helps the sink discriminate the signal reflected by the node from other reflections from the surrounding environment, which would not rotate the signal polarization. Finally, the retrodirective millimeter wave antenna array does not use RF signal amplifiers for low power operation, which increases the node lifetime or energy harvesting requirements. In this basic configuration, the tag can be employed to locate and track assets when used with a radar-like sink.

In a more advanced configuration, the retrodictive millimeter antenna array further incorporates a switching mechanism which can be used to implement on-off keying modulation of the reflected signal. This modulation technique can enable the RF node to transmit information back to the sink without employing power amplifiers, which is one of the main sources of energy consumption in sensor nodes. Note that the use of millimeter wave operation reduces the array size, and thereby the node size, improves the localization accuracy, and increase the achievable data rate for RF node communications of collected data. In the following section, we describe in detail the switching retrodirective millimeter wave antenna array, also referred as a tag, concept.

B. RETROREFLECTION CONCEPT AND TAG STRUCTURE

A Van-Atta array [8] is formed by grouping individual elements in the array with delay lines of same electrical length such that it results in a symmetric array with respect to its center as shown in Fig. 2(a). This configuration allows to achieve a phase conjugation that results in opposite phase front directions for the incident and reflected signals, thereby
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FIGURE 1. Retrodirective sensor node concept.

FIGURE 2. Retroreflective tag (a) Van-Atta array description, (b) Required FoV [18].

The reflected signal is in the same direction as the incident signal.

The FoV of a Van-Atta array depends on the elements’ radiation characteristics and inter-element distance. As shown in Fig. 2(b), smaller the inter-element distance (d), larger will be the array FoV. To cover various application requirements, we target an azimuth plane FoV of 120° over which the tag is required to have retroreflective characteristics in this plane. In the perpendicular plane (elevation), the FoV should be narrow to avoid unwanted reflections from the ground and overhead installations. To realize the tag considered in this article, a 9° elevation FoV is selected. To achieve this elevation plane FoV, each individual element of the retroreflective array requires to have a 9° half power beam width (HPBW). Of course, it is assumed that the tag reader would operate in the azimuth plane, with elevation close to 0°. For wider FoV in azimuth, individual elements should also have a wide radiation pattern in YZ-plane, hence, having a fan beam shaped radiation pattern. In addition to the FoV requirements, we selected the 77-81 GHz band for the tag operation.

The elements used to realize the retroreflective array are shown in Fig. 3. The structure dimensions are given in Table 1 and are described in details in [19]. The structure of the radiating elements with orthogonal polarization and its dimensions along with the performance characterization are given in this article. The structure with X polarization (X-pol) and Y polarization (Y-pol) are shown in Fig. 3(a) and (b), respectively, with respect to the coordinate system in the figure. These elements consist of cavities fed by an underlying SIW. The cavities are coupled to the SIW by slots on their bottom wall, and radiate through slots on their upper wall. Cavity backed slot radiators available in the literature [20]–[22] use cavities resonating in higher order modes which results in
The X-pol and Y-pol 1D arrays were designed and fabricated to validate the building block of the tag [19]. The measured $S_{11}$ for the X-pol and Y-pol 1D arrays represented in Figs. 3(c) and 3(d) are shown in Fig. 5(a). The measured radiation patterns are shown in Fig. 5(b). All the components of the tag were designed at 77 GHz however, up to 3% operating frequency shift was observed in the fabricated prototypes due to dielectric constant variation and fabrication tolerances. These measured results show that the 1D arrays, which are the building blocks for retroreflective array, have a 2 GHz $-10$ dB $S_{11}$ bandwidth and fan beam radiation patterns. The radiation patterns, in the plane of the array axis, provide $10^\circ$ and $9^\circ$ of HPBW for the X-pol and Y-pol arrays, respectively. In the perpendicular plane, the Y-pol array provides wide radiation pattern whereas the X-pol array provides nulls at $\pm90^\circ$. This radiation pattern can be explained by considering the fact that a radiating slot is a magnetic dipole which has omnidirectional pattern in plane perpendicular to the slot axis (Y-pol plane in this case). Whereas, this dipole

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**TABLE 1. Van-Atta Array Building Block dimensions (in mm).**

| Parameter             | Dimensions |
|-----------------------|------------|
| Cavity size           | $1.7 \times 1.5$ |
| SIW feed width        | 1.63       |
| SIW feed length       | 20.2       |
| X-pol radiation slot  | $1 \times 0.2$ |
| X-pol feed slot       | $1 \times 0.15$ |
| X-pol radiation slot  offset | 0.1        |
| X-pol feed slot offset | 0.2        |
| Y-pol radiation slot  | $0.81 \times 0.2$ |
| Y-pol feed slot       | $1 \times 0.15$ |
| Y-pol radiation slot  offset | 0.13       |
| Y-pol feed slot offset | 0.1        |

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**FIGURE 4.** Description of the proposed retrodirective tag.
produces nulls at ±90° for plane parallel to the slot axis (X-pol). These patterns define the tag backscattering response in the azimuth plane which will be, ideally, the product of these two radiation patterns and the array factor squared.

The next step was to design the delay lines to implement the retrodirective function. These lines are U-shaped SIW transmission lines with width of 1.76 mm in a 0.508 mm thick substrate ($\varepsilon_r = 2.94$). The transmission coefficient phases of all eight lines simulated with Ansys-HFSS are shown in Fig. 5(a). At the design frequency (77 GHz), all the lines almost have same phase. The simulated phase for all the arms is in a range of 6.2°. Elimination of this variation requires small adjustments in the line lengths that may be difficult to control accurately in practice. With deviation from this frequency, a squint is expected in the reflected back beam due to phase variation because of unequal physical lengths. This beam squint is quantified in Fig. 5(b) for broadside incidence on the tag. For this figure, simulated magnitude and phase of the delay lines’ transmission coefficient ($S_{21}$) were used in the following array factor expression to determine the beam squint variation with frequency:

$$AF(\theta) = \sum_{n=1}^{8} A_ne^{jknd\sin\theta + \alpha_n}; \quad -90° \leq \theta \leq +90°$$

where $A_n$ and $\alpha_n$ represent, respectively, the magnitude and phase of the transmission coefficient of the $n^{th}$ delay line. $k$ is the free-space wavenumber, $n$ is an integer ranging from 1 to 8 representing each antenna element in the array, $d$ is the spacing between the antenna elements and $\theta$ is an independent variable in the AF varying from −90° to +90°. It can be derived from this figure that around the design frequency, the reflected beam squints with an approximate rate of 22°/GHz.

It is important to mention that the phase slope of the line increases with its length. Hence, the alternated lines configuration, that reduces the physical length of the delay lines, helps to decrease the rate of beam squint.

### D. SWITCH CONCEPT

On-off modulation of the reflected beam in the proposed tag can have several advantages such as adding extra information and increasing the signal to noise ratio (SNR) for signal processing at the receiver. In this regard, a switch can be introduced in the delay lines as shown in Fig. 4, adding amplitude modulation in the reflected signal, as presented in [25]. This way, an analog voltage generated by a sensing module can be applied to a modulating circuit controlling the switches on the delay lines. A simple form of load on SIW can be realized for this purpose by inserting a slot on the SIW as shown in Fig. 7(a). A centered slot on the broadside of a rectangular waveguide, inclined with respect to the line axis, provides a series load that is maximum when the slot is oriented perpendicular to the axis [26]. This high impedance reflects back the signal and cause low transmission. The slot impedance can be switched between ON and OFF states by loading the slot with a PIN diode. Such a fully functional switch in K-band, presented in [27], provides at least 10 dB amplitude variation between the two switch states.

It is important to mention that the proposed switch, along with its biasing circuitry, fits within the width of the SIW.
Therefore it can be easily integrated in the proposed retroreflective tag. The switch and its biasing network, as presented in [27], are shown in Fig. 7(c). A very thin laminate is placed on top of switch slot. The diode, placed on this laminate along with its biasing network, is coupled with the slot due to parasitic capacitance realized by the thin laminate. The laminate also contains the biasing network which is quite compact due to high operating frequency. This switch, which can be installed on top of an SIW along with is biasing network, is suitable to be integrated in the feeding lines for the proposed retrodirective tag.

To emulate the operation of an ideal PIN diode in W-band, a hardwired switch was prototyped as shown in Fig. 7(b). In the off-state switch case, a resonant slot is placed on an SIW. The measured S parameters of this SIW are presented in Fig. 8(a) showing at least 12 dB of isolation in the band of interest. For on-state switch, the slot is shorted at middle, representing a forward biased PIN diode. The measured S parameters of the on-state switch along with a reference SIW line of same length, as shown in Fig. 8(b), exhibit negligible insertion loss for the proposed switch. In addition to the measured hardwired switch response, the proposed switch is also simulated with realistic W-band PIN diode model presented in [28] with 1 μm² anode surface area. The simulated on- and off-state switch responses are shown in Fig. 8(c). Though the parasitic capacitance of the realistic model slightly degrades the off-state switch isolation, it is still higher than 10 dB in band of interest. The diode series parasitic resistance does not affect the proposed switch performance. Thus, a diode loaded slot on an SIW acts as a switch that can be used for amplitude modulation of the reflected signal.

This type of switch can be included in the tag structure by introducing the switch slots on the delay lines at the back side of the tag as shown in Fig. 4. To measure the performance of this switch, monostatic backscattering of the tag prototypes with and without switch slots are compared in the following section. A tag prototype with switched slots can easily be converted to a fully operational amplitude modulating tag, provided a PIN diode is accessible in W-band.

III. FABRICATION AND MEASUREMENTS

The RT/Duroid 6002 substrate from Rogers Corporation with 0.508 mm thickness was used to fabricate the tag, and the
structure was optimized in Ansys-HFSS. The nominal dielectric constant ($\epsilon_r$) and loss tangent of this substrate in X band are 2.94 and 0.0012, respectively, as indicated by the manufacturer. However, since our design is in the W-band, it was estimated by measuring the resonance of an SIW cavity that the dielectric constant is about 7% lower than the specified value. Hence, in comparison with the simulations, an upshift in the operating bands of the fabricated prototypes is expected as observed in [19]. Similarly, the insertion loss measurements of a straight SIW line revealed that an SIW designed in the W-band is 0.52 dB/cm lossier than in the X-band [23], causing additional losses in the fabricated prototypes. Metal roughness also contributes to about 10% loss in the measurements [29].

The tag structure consists of two layers. The bottom layer contains the SIW feed of the 1D array elements and the delay lines. The cavities, which excite the radiating slots, are supported by the second layer (Fig. 3). The feeding slots, in between the two layers, couple the feed network with the cavities [19]. The two layers were fabricated separately and then assembled together with 5 micron adhesive layer in between, cured under high temperature and pressure.

The cavities and feeding network (1D array feeding SIW and delay lines) are realized by electroplating the walls of a slot formed by laser machining through the substrate. The coupling and radiating slots are fabricated by etching out the copper cladding treated with a photosensitive mask. Two tag prototypes, one without and the other with switch slots, were fabricated as shown in Fig. 9. The measurement setup and tag characterization are discussed in the next section.

**A. MEASUREMENT SETUP**

A setup was established to measure monostatic and bistatic scattering properties of the tag as shown in Fig. 10. This apparatus consists of a manually controlled turntable on which the tag is installed. This turntable pivots the tag by an angle $\chi$. A rotating arm holds the transmitter (Tx) on its other end, placing the transmit horn antenna at a distance of 72.5 cm from the pivot of the tag, and can rotate the transmitter by an angle $\theta$ with respect to the normal of the pivoted tag. A receiver (Rx) horn antenna is at a fixed position, at a distance of 75 cm from the tag pivoting axis. The transmitter is installed slightly lower than the receiver to avoid hinderance with the receiver while rotating the transmitter arm. Hence, as the tag is not placed at the maximum gain position of the antennas, this Rx-Tx configuration is expected to lower the reflected signal due to directive radiation patterns of the horn antennas. The tag height is carefully adjusted to ensure that the tag is in the horn antennas’ HPBWs during the whole measurement process.

The polarization of the transmit horn antenna is rotated by 90° around its axis using a waveguide twist. Hence, the transmitter and receiver have vertical and horizontal polarizations, respectively, in reference to the base of the measurement setup. Both horn antennas (QRR-WOOY75), manufactured by Quinstar, have a measured gain of 25 dB, and 23 dB of measured cross-polarization isolation. This finite cross-polarization isolation affects the measurements around the broadside of the tag as discussed in the following section.

The horn antennas are connected with Virginia Diodes W-band vector network analyzer extenders connected to Keysight PNA-X N5247A vector network analyzer (VNA). The system is calibrated till the end of the network analyzer’s extenders for the 75-83 GHz band. The process for monostatic and bistatic scattering measurements is illustrated...
in Fig. 10(b) along with characterization of the elevation FoV. For monostatic measurements, Tx and Rx antennas are stationary at $\theta = 0^\circ$ and the tag is rotated on the turntable. It is equivalent to rotating the transmitter and receiver together from $\theta = -60^\circ$ to $\theta = +60^\circ$ in $1^\circ$ steps as shown in Fig. 10(b). The transmission coefficient $S_{21}$ is recorded for the whole VNA calibration frequency band. This coefficient corresponds to the cross-polarized scattering behavior of the tag. It is important to mention that 75 cm range limitation is due to limited transmitted power ($\approx 0 \text{ dBm}$) and dynamic range ($\approx 65 \text{ dB}$) of the VNA in the desired frequency band. Higher transmitted power, better dynamic range, and the use of an LNA in the tag as in [1] will allow to increase the distance between the tag and Tx/Rx antennas.

Strong structural reflection at the broadside of the tag is used to calibrate the system. Keeping the Tx and Rx antennas pointing in the same direction, the tag is rotated on the turntable to maximize the measured $S_{21}$. The common direction of the Tx and Rx antennas is then taken as the $\theta = 0^\circ$ reference. For bistatic scattering measurements (Fig. 10(b) bistatic case), the receive antenna is fixed and the tag is positioned at an offset angle $\chi$. The receive antenna is therefore at $\theta_r = \chi$, where $\theta_r$ is the position of the receiver antenna with respect to the reference ($\theta = 0^\circ$). The transmitter is then rotated around the tag pivot from angle $\theta = -60^\circ$ to $\theta = 60^\circ$.

First, the setup is calibrated as mentioned in the monostatic case and then the tag is rotated at an angle $\chi$. The transmitter reference angle ($\theta = 0^\circ$) is set in the direction normal to the tag, as shown in Fig. 10(b), for better presentation of the measured data. In the following text, the measured monostatic cases correspond to the $S_{21}$ parameter obtained when the Tx and Rx antennas point in the same direction, that is when $\theta_r = -\theta$.

**B. MEASUREMENTS OF FABRICATED PROTOTYPES**

In order to characterize the frequency response of the tag at different incident angles, measured monostatic $S_{21}$ as a function of frequency is plotted in Fig. 11 for various values of $\theta$. The retroreflective RCS bandwidth is very narrow, mainly due to unequal physical length of the delay lines that satisfy the Van-Atta condition of equal electrical length for a single frequency. This figure shows that the maximum $S_{21}$ response is near 78.6 GHz for different $\theta$ values. Hence, it can be assumed that it is the frequency at which the phase conjugation condition is better satisfied. It was chosen as the measurement frequency for scattering behavior graphs shown in the rest of this section. The difference between the design frequency and best measured retrodirective frequency is due to the inaccuracy of the nominal permittivity of the substrate used in simulations. At W-band, the effective permittivity is smaller than the specified X-band value. Therefore a higher frequency is necessary to achieve equalized phases.

The proposed retroreflector was simulated in Ansys-HFSS to estimate its RCS at the design frequency (77 GHz). The simulated monostatic RCS is presented in Fig. 12 along with the measured monostatic $S_{21}$ response of the designed tag and $0.3 \times 0.3m^2$ flat aluminium sheet. An absolute comparison between the measured $S_{21}$ and simulated RCS is not fair as in the simulations the tag is illuminated with a uniform plane wave whereas in measurements, high gain horn antennas causing non-uniform illumination are used at short distance due to limited available radiated power. Nevertheless, the measurements qualitatively exhibit the flat scattering response of the tag. Both simulated RCS and measured tag $S_{21}$ responses show wide FoV. Additionally, a spike is observed in the measurements near the broadside direction ($\pm 5^\circ$). This spike is due to the limited cross-polarization isolation between the transmit and receive horn antennas in the measurement setup, allowing the reception of strong structural reflections at broadside with cross-polarized receive antenna. It is not the case for the simulated RCS as it assumes infinite isolation between incident and reflected signal polarization. Practically, a polarizer should be used with the Rx antenna to provide better H-pol to V-pol isolation. The tag $S_{21}$ is at least 15 dB higher than that of the flat aluminium sheet for almost the whole $120^\circ$ FoV, except near the broadside direction. The metal sheet emulates electrically large targets positioned at a short distance form the radar transmitter. The significantly enhanced retrodirective property of the tag is observed compared to that of the plate outside the plate main scattered beam.

**FIGURE 11.** Normalized measured monostatic scattering from the tag with respect to the frequency at different $\theta$.

**FIGURE 12.** Simulated tag RCS (at 77 GHz) along with the measured monostatic scattering (at 78.6 GHz) of the tag and $0.3 \times 0.3m^2$ metal sheet.

Simulated bistatic RCS of the tag for different $\chi$ values (Fig. 10(b)) is shown in Fig. 13. This simulation shows that the maximum RCS is obtained when $\theta = -\chi = -\theta_r$ and...
that grating and side lobes of the reflected beam for each $\chi$ are 10 dB below the main beam except for the cases $\chi = +/ - 60^\circ$ where the 10 dB objective is not reached. The reduction of the RCS with increase in $|\chi|$ is mainly due to the radiation pattern of X-pol 1D array in this plane (left graph in Fig. 5(b)) specially for $|\theta| > 50^\circ$. Sidelobes for smaller values of $\theta$ are less affected by this reduction, which makes the relative peak-to-sidelobe level slightly below 10 dB for the large $|\chi|$ cases.

FIGURE 13. Simulated bistatic RCS of the tag at 77 GHz for different values of $\chi$.

Measured bistatic $S_{21}$ behavior for $\chi = 40^\circ$ for four different frequencies is shown in Fig. 14. Considering the $S_{11}$ response of the 1D arrays (Fig. 5(a)), the elements start radiating between 78 GHz and 78.6 GHz. It is at this last frequency at which we have the maximum monostatic RCS in Fig. 14. The band below 78 GHz is outside the impedance bandwidth of the radiating elements. Within the impedance bandwidth of these elements, the reflected beam squint increases with the frequency. However, the gain of the reflected beam reduces with increase in the squint angle due to X-pol elements’ radiation pattern. From 78.6 GHz to 79.2 GHz, the reflected beam squint is approximately $13^\circ$, which is at almost the same rate ($22^\circ /\text{GHz}$) as predicted with the help of the simulated $S_{21}$ magnitude and phase of the delay lines (Fig. 6(b)).

FIGURE 14. Measured tag bistatic $S_{21}$ variation with frequency for $\chi = 40^\circ$.

The phase characteristics of the fabricated delay lines can also be investigated by observing bistatic $S_{21}$. As shown in Fig. 14, for $\chi = 40^\circ$, the bistatic $S_{21}$ response is maximum at approximately $\theta = -47^\circ$ when $f=78.6$ GHz. Using the estimated beam squint rate and the measured beam squint angle of $7^\circ$, it can be deduced that the delay lines provide equal electrical length condition at about 78.3 GHz, which is outside the impedance bandwidth of the radiating elements. In addition to the effect of frequency shift mentioned in the previous paragraph, squint can also come from delay lines phase errors due to the fabrication tolerances. The delay lines electrical length is quite sensitive to SIW width that determines the guided wavelength inside the SIW. Simulations show that for SIW width variation, as small as 25 microns, the frequency at which the designed delay lines have an equal transmission phase shifts by about 400 MHz.

Bistatic $S_{21}$ is measured at different $\chi$ values, as shown in Fig. 15. Each curve has a label indicating the expected maximum position at $\chi = -\theta$ for retrodirective operation. However, due to the phase shift error in the delay lines, the direction of the reflected beam is different than expected. The amount of beam squint can be calculated with equation 1.

FIGURE 15. Measured bistatic $S_{21}$ at 78.6 GHz for four different values of $\chi$.

These predicted beam squint angles are marked in Fig. 15 with labels $P_\chi$. It can be seen that this phase error in the delay lines is causing a loss up to 4 dB between the maximum measured reflection level (point $P_\chi$) and the level measured at the expected angle ($\theta = -\chi$).

The elevation plane characteristics of the tag can be evaluated by measuring the tag monostatic $S_{21}$ response with different inclination angle ($\zeta$) values (Fig. 10(b)). The measured response is shown in Fig. 16 with inclination angle $\zeta$ specified in the figure. This figure shows that $S_{21}$ decreases monotonically with increase in angle $\zeta$. This verifies the elevation beamforming characteristics of the proposed tag structure illustrated by the XZ-plane patterns of Fig. 5(b).

FIGURE 16. Measured $S_{21}$ variation at 78.6 GHz with different inclination angles.
Switching characteristics can easily be added in the proposed tag by introducing a switch slot in the delay lines as shown in Fig. 4 and 9(b). To illustrate this, two ideal switch states were realized by fabricating two tag prototypes, one with and another without switching slots. The monostatic $S_{21}$ response of the two prototypes is shown in Fig. 17. Outside the strong structural reflection region near $\theta = 0^\circ$, the difference between the two cases is approximately 15 dB, which corresponds to the switch isolation presented in Fig. 8(a). This validates the amplitude modulation potential of the proposed tag by using switching slots in the delay lines.

![Switching Characteristics](image)

**FIGURE 17.** Measured monostatic scattering at 78.6 GHz with and without switch slots.

A comparison is presented in Table 2, highlighting key features of the tag presented in this work. The orthogonal polarization and amplitude modulation capacity are incorporated in the tag while limiting the inter-element spacing. This limited inter-element spacing is important to maintain retroreflection for wider FoV of the tag as demonstrated by the measured $S_{21}$ and simulated bistatic RCS presented in this work.

| Ref. | Freq. (GHz) | Inter-ele. spacing | Pol. Rotat. | Amp. Mod. | Calculated FoV (Grat. lobes < -10dB) |
|------|-------------|---------------------|-------------|-----------|-------------------------------------|
| [9]  | 26          | 0.8λ                | No          | Yes       | 16°                                 |
| [10] | 30          | 0.73                | No          | Yes       | 36°                                 |
| [15] | 79          | 0.79λ               | Yes         | No        | 20°                                 |
| [16] | 1.27        | 0.7λ                | Yes         | No        | 34°                                 |
| This work | 78.6     | 0.48λ               | Yes         | Yes       | 70° (From Fig 15)                   |

Large inter-element spacing can result in higher boresight directivity as compared to compactly packed array but the directivity is lower if wide angle beam scanning is considered. Theoretical calculations show that an 8-element array with 0.48λ spacing results in 8.9 dB for broadside beam directivity, and 9.1 dB directivity for beam scanned at 60°. For array with 0.8λ spacing (as in refs.), directivity is 10.9 dB for broadside beam, and 8.2 dB for beam scanned at 60 degrees. However, this changes if we consider arrays of the same physical dimensions. Suppose an array of 8 elements spaced by 0.48λ, so the overall size will be approximately 4λ. If the spacing is 0.8λ the array would have only 5 elements. In this case, the directivity of the broadside beam is 8.7 dB (versus 8.9), but it falls to 6.2 dB (versus 9.1) when the beam is scanned at 60 degrees. So it can be seen that for arrays of same electrical size, the finer spacing gives better directivity when scanning. In addition, the finer spacing array has no grating lobes, which reduces interference and ambiguities.

**IV. CONCLUSION**

A retroreflective tag design featuring improved backscattering, amplitude modulation, orthogonal incident and reflected polarization states and wider FoV with suppressed grating lobes is introduced in this article. The tag design procedure is presented with the description of the radiating elements, elevation plane beamforming arrays and delay lines connecting the radiating elements to form a retroreflective array. A switch concept is also proposed for amplitude modulation in the reflected signal. A measurement apparatus and procedure were also established to measure cross-polarized monostatic and bistatic scattering. The designed tag achieved approximately 120° FoV while limiting the grating lobes under −10 dB level with respect to the main beam. The FoV is doubled compared to that of previously reported mm-wave retrodirective arrays. The 26.5 dB measured gain of the arrays used in the tag design improves the tag backscattering without using active RF circuits. The tag prototype exhibited almost 15 to 20 dB higher monostatic reflection in comparison to a flat metal sheet. Using the measured bistatic $S_{21}$, the radiating elements and error in the delay lines of the fabricated prototype were also characterized. The elevation FoV is also evaluated by introducing an inclination angle between the tag prototype and transmit and receive antennas. Monostatic $S_{21}$ variation of almost 15 dB was observed by inserting a switch in the delay lines. This allows for scattering modulation, therefore enhancing the functionality of the tag. An absolute comparison between the RCS simulations and $S_{21}$ measurements is not relevant as mentioned in Section III-B, however, both exhibit similar scattering behaviours. Although the measured results demonstrate the validity of the proposed tag concept, they highlight the necessity for an accurate characterization of the substrate material in the W-band and a well-controlled fabrication process in order to minimize the beam squint and frequency shift effects.

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