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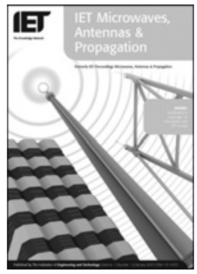

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A 60 GHz retrodirective array system with efficient power management for wireless multimedia sensor server applications

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Abstract: A 60 GHz retrodirective array system with efficient power management for wireless multimedia sensor server applications is proposed. The system consists of three sections: a retrodirective array, a local oscillator (LO) and a power management system. The proposed system is able to efficiently control battery power by turning off when it is not in use. In particular, the power management circuit controls the power of the LO by a rectenna for efficient battery operation. Although there is no interrogating signal, the system is in a sleeping mode where extremely low power consumption occurs. When the system is interrogated by an RF signal, the system is awaken and starts consuming full power. When the received power density is larger than 0.013 mW/cm^2, the system turns on and starts working as a retrodirective array. Furthermore, the proposed system can avoid the use of an expensive LO by employing a fourth subharmonic mixer. Experimental data are used to verify the proposed idea.

1 Introduction

The recent advance of multimedia electronic devices, such as CMOS cameras and microphones, has paved the way for wireless multimedia sensor networks (WMSNs), where each node is wirelessly communicating and transferring multimedia data [1–3]. For example, a wireless sensor server collects the data obtained from wireless sensors in an environment monitoring application. However, such systems require reliability, high data rate, security and privacy. The high data rate requirement can be achieved by utilising broadband frequency bands such as the 60 GHz band [4].

Because of the broad and licence-free bandwidth, the 60 GHz bands are highly utilised for wireless multimedia applications [5, 6]. A 7 GHz bandwidth in the range from 57 to 64 GHz is assigned in the USA, whereas 59–66 GHz in Japan. In addition to the high data rate in this spectrum, the 60 GHz band has specific atmospheric attenuation. As a result of oxygen absorption, a signal cannot propagate far so that this spectrum becomes a good candidate for short-distance communication in terms of privacy and interference requirements.

It was previously shown in [7] that a digital wireless sensor server can be implemented with a retrodirective array, where a received RF signal can be retransmitted towards the source without any information of the source location. In this paper, we present a 60 GHz retrodirective array system for WMSN applications. Since low power consumption is a major issue in a wireless sensor network, a novel efficient power management scheme is introduced in the proposed system.

Recently, a novel power controllable retrodirective array system for 5.8 GHz operation where a received RF signal activates the bias of the amplifier in an efficient manner was proposed by the authors [8]. This concept can be applied to the 60 GHz retrodirective array [9] to control the local oscillators (LOs) bias instead of the amplifiers' bias. Since the received power at 60 GHz is much weaker than at 5.8 GHz, a more sensitive power management scheme is required to trigger the system. Therefore the analogue switch in [8] is replaced with a zero-cross detector which activates when the input voltage is larger than zero. Nevertheless, the proposed system still consumes extremely low power in sleeping mode and triggers to a working mode when an RF signal is received. The proposed idea is successfully demonstrated in [10] and the complete system will be further studied in this paper.

This paper is organised as follows. In Section 2, the principle of the proposed system is discussed. This system consists of a retrodirective array and a novel power management scheme, which are described in Sections 3 and 4, respectively. In Section 4, the operating principle of the power management is first explained and then its performance is discussed. The experimental results of the overall system are reported in Section 5. Finally, conclusions are drawn in Section 6.

2 Principle of system operation

As shown in Fig. 1, the proposed system consists of two sections; a retrodirective array section and a power management section. The power management section is composed of a rectenna, a zero-cross detector and a battery. In the proposed system, external power is used instead of a battery for demonstration of the proposed idea.

In general, a retrodirective array has several active devices so that it consumes battery power consistently. As the number of elements in the array increase, it consumes more DC power. In the proposed system, the power management section is inserted in order to efficiently control the active devices' bias. This enables active devices to consume DC battery power only when an RF signal is received. This idea is useful for a retrodirective array because it operates when an RF signal is received for its beam steering capability. Therefore the proposed system consumes DC battery power only when it needs to operate. The proposed scheme becomes more efficient if the system is rarely used.

The block diagram in Fig. 1 explains how the proposed idea works. Initially, the retrodirective array is disconnected to a battery so that it consumes extremely low-DC power from a zero-cross detector. This off state is referred to as the sleeping mode. Once an RF signal is received, it is converted to a DC signal by the rectenna. If this DC voltage is larger than a reference DC voltage (ideally zero volts) of the zero-cross detector, the retrodirective array is connected to the battery and consumes DC power. This on state is referred to as the active mode. When the RF signal is no longer detected or less than a certain level, the system goes back to the sleeping mode.

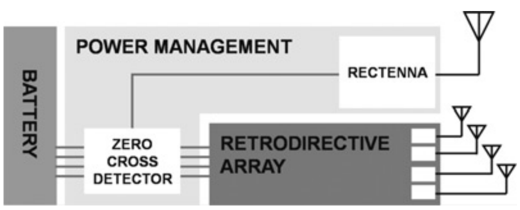

Figure 1 *Block diagram of the proposed system*

In the proposed system, DC power is consumed from amplifiers and an LO. Since it was demonstrated that a 5.8 GHz retrodirective system can control the bias of amplifiers, in this paper it will be shown that a 60 GHz retrodirective system can control the LO's bias.

In the following sections, each part will be further studied and experimental results will be presented to evaluate the proposed system's performance.

3 A 60 GHz retrodirective array

In this paper, the phase conjugation retrodirective array is implemented by way of heterodyne mixing since it is compatible to electronic devices [11]. For phase conjugation with heterodyne mixing, the LO frequency is typically supplied at twice the RF frequency. In this configuration, a single mixer is used and the phase-conjugated signal is obtained by taking the lower sideband signal in (1)

$$\begin{aligned} V_{IF} &= V_{RF}\cos(\omega_{RF}t + \theta_n) \times V_{LO}\cos(\omega_{LO}t) \\ &= \frac{V_{RF1}\cdot V_{LO}}{2}\left[\cos((\omega_{LO} - \omega_{RF})\cdot t - \theta_n)\right. \\ &\quad \left. + \cos((\omega_{LO} + \omega_{RF1})\cdot t + \theta_n)\right] \end{aligned} \quad (1)$$

where θ_n is phase at nth antenna element.

However, since RF/IF isolation is poor with a single mixer, pair of mixers is used to suppress the incoming RF signal. In this scheme, the phase conjugating can also be achieved with subharmonic mixers [12, 13] and fourth subharmonic mixers [9]. Because of the anti-parallel diode pairs (APDs), the LO frequency at one-fourth of the RF frequency is required for the down-converter and up-converter mixers. It will be economical to use a fourth subharmonic mixer for a heterodyne mixing at 60 GHz frequency bands, since it is difficult and expensive to use an LO operating at twice of RF frequency.

Fig. 2 shows the block diagram of the system using the fourth subharmonic mixer. From the heterodyne mixing, the phase-conjugated signal can be obtained by taking the lower sideband frequency, which is the IF of the first mixer. In order to transmit only the phase-conjugated signal, the down-converter is followed by a low-pass filter (LPF) which filters out undesired signals, and a second mixer to up-convert the signal to the RF band. The LO frequency is typically supplied at twice the RF frequency. Finally, a phase-conjugated signal from a pair of mixers is

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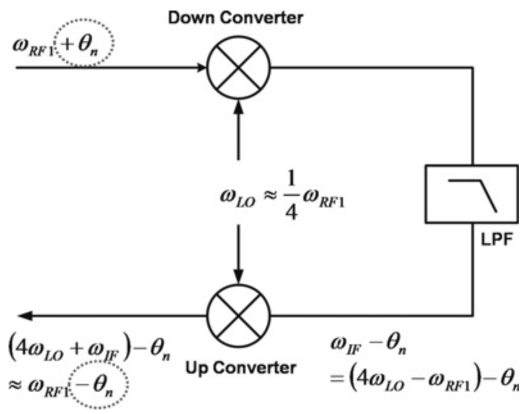

Figure 2 *Block diagram of the fourth subharmonic phase conjugation*

given by

$$
\begin{aligned}
V_{\mathrm{IF}} &= V_{\mathrm{RF1}} \cos(\omega_{RF1} t + \theta_n) \times V_{\mathrm{LO}} \cos(4\omega_{\mathrm{LO}} t) \\
&= \frac{V_{\mathrm{RF1}} \cdot V_{\mathrm{LO}}}{2} [\cos((4\omega_{\mathrm{LO}} - \omega_{\mathrm{RF1}}) \cdot t - \theta_n) \\
&\quad + \cos((4\omega_{\mathrm{LO}} + \omega_{\mathrm{RF1}}) \cdot t + \theta_n)]
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
V_{\mathrm{RF2}} &= \frac{V_{\mathrm{RF1}} \cdot V_{\mathrm{LO}}}{2} \cos((4\omega_{\mathrm{LO}} - \omega_{\mathrm{RF1}}) \cdot t - \theta_n) \\
&\quad \times V_{\mathrm{LO}} \cos(4\omega_{\mathrm{LO}} t) \\
&= \frac{V_{\mathrm{RF1}} \cdot V_{\mathrm{LO}}}{2} \cos(\omega_{\mathrm{IF}} t - \theta_n) \times V_{\mathrm{LO}} \cos(4\omega_{\mathrm{LO}} t) \\
&= \frac{V_{\mathrm{RF1}} \cdot V_{\mathrm{LO}}^2}{4} [\cos((4\omega_{\mathrm{LO}} + \omega_{\mathrm{IF}}) \cdot t - \theta_n) \\
&\quad + \cos((4\omega_{\mathrm{LO}} - \omega_{\mathrm{IF}}) \cdot t + \theta_n)]
\end{aligned} \tag{3}
$$

The fourth harmonic retrodirective array is fabricated on the alumina substrate ($\varepsilon_r = 9.8$, $h = 5$ mils) for a 60 GHz signal line and duroid substrate ($\varepsilon_r = 10.2$, $h = 10$ mils) for a 15 GHz and DC bias lines. In the proposed system, 61.33 GHz was chosen as the receiving RF frequency and 15.3575 GHz as the LO frequency. Then, the down converted IF, 200 MHz is again up-converted to 61.53 GHz and undesired signals are eliminated by a LPF. Agilent beam lead schottky diode pairs (HSCH-5531) are employed for the APDPs in up-/down-converters. Since the mixers are using the fourth harmonics, the measured conversion loss is more than 14 dB. The up- and down-converters are optimised to a LO power of 2 dBm. In this system, four pairs of phase conjugators are implemented for the retrodirective array. Finally, the conjugated phases from four elements are transmitted and the beam direction is determined by an array factor. As a data recovery sensor, a baseband data can be extracted after the LPF.

In order to compensate for propagation loss and conversion losses of the up-/down-converters, Velocium V-band monolithic microwave integrated circuit (MMIC) low noise amplifier (LNAs) (ALH 382-0) are used before the down-converters and after the up-converters. These LNAs and the LO are consuming power even if the retrodirective array system is not interrogated. Therefore a power management scheme is required for the efficient battery operation.

4 Power management scheme

The power management scheme is introduced to control the bias of the LO in the retrodirective array system. The proposed schematic of the overall system is illustrated in Fig. 3. The power management scheme consists of a rectenna and a zero-cross detector. The rectenna and zero-cross detector are individually implemented and then combined together. In this section, the rectenna and the zero-cross detector are introduced and their performance is investigated.

4.1 Rectenna technology

A rectenna is a combination of a rectifier and an antenna. Typically, a rectenna is composed of an antenna, a band-pass filter (BPF), a rectifier and an LPF [14–16]. When an RF signal is received by the antenna, undesired signals are filtered out through the BPF. The filtered RF signal is converted to DC power by the rectifier. The antenna for the rectenna can be chosen depending on the intended application; broadband operation [14], dual-frequency operation [15] or circular polarisation [16].

In the proposed system, a circular sector antenna is selected in order to simplify the rectenna configuration. It was reported that an antenna with 240° of a circular sector angle and 30° of a feeding angle from the edge has the second and third harmonic rejection capability [17]. Because of this unique harmonic suppression characteristic of the circular sector antenna, the BPF between the antenna and the rectifier can be eliminated so that the rectenna can be simplified and high conversion efficiency can be further achieved [18].

The layout of the proposed rectenna is illustrated in Fig. 4. As seen in Fig. 4, two diodes are connected in series in order to add up each voltage since higher voltage is more critical than higher DC power for triggering the zero-cross detector.

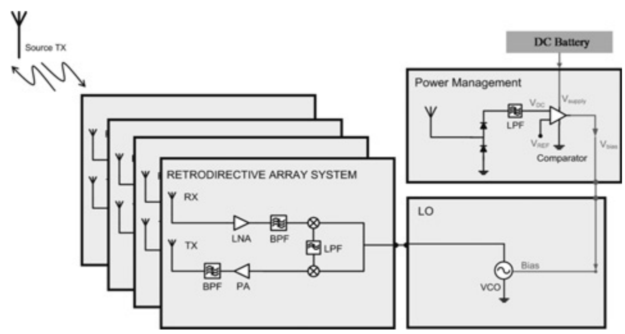

Figure 3 *Proposed schematic of the overall system*

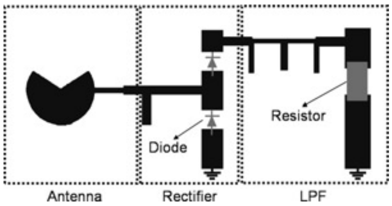

Figure 4 *Layout of the proposed rectenna*

4.2 Zero-cross detector

As frequency increases, transmission loss becomes higher. Because of the atmosphere attenuation at 60 GHz, the trigger mechanism for the power management needs to be more sensitive than that for other microwave bands.

In the proposed power management, a zero-cross detector is placed between a battery and a bias network. The zero-cross detector is a type of comparator as depicted in Fig. 5. When an input DC signal is larger than a reference signal, DC power from the battery is supplied to the retrodirective array. In the case of a zero reference voltage, it is referred to as a zero-cross detector because it turns on when the signal is larger than zero. Therefore the sensitivity of the power management is dependent on the zero-cross detector.

Compared with the analogue switch used in the previous 5.8 GHz power management system [8], sensitivity is improved by replacing the analogue switch with a zero-cross detector, while sacrificing power consumption in an idle mode. However, since modern technology for analogue comparator enables ultra-low supply currents, the idle power consumption is still negligible.

4.3 Implementation of power management scheme

The power management scheme is implemented by combining the rectenna and the zero-cross detector. The rectenna is built on alumina substrate ($\varepsilon_r = 9.8$, thickness = 5 mils) for low-loss RF signal line and the zero-cross detector is built on duroid substrate ($\varepsilon_r = 10.2$, thickness = 10 mils) for the DC signal line.

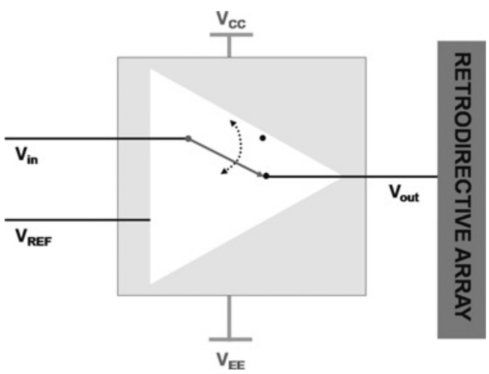

Figure 5 *Zero-cross detector*

For the rectenna, a circular sector antenna is first designed at 61 GHz by using Agilent advanced design system (ADS) momentum. The simulated return loss is shown in Fig. 6. The second and third harmonic frequencies are successfully suppressed as illustrated in Fig. 6. In order to rectify an RF signal to a high DC voltage, two Agilent detector diodes HSCH-9161 are connected in series so that the output voltage is doubled. It is important to choose a proper load resistance for an efficient power management. The output voltage of the rectenna needs to be as high as possible, while keeping a minimum power to operate a zero-cross detector. Higher load resistance equates to higher output voltage. In the proposed rectenna, a 10 MΩ chip resistor is used for this reason.

For the zero-cross detector application, a maxim comparator (MAX-9117) is selected because of its ultra low supply currents (600 nA). Ideally, a comparator can work as a zero-cross detector with the grounded reference port ($V_{REF} = 0$ in Fig. 5). However, the reference voltage needs to be tuned due to the unstable ground of the circuit in practice. In the test environment, V_{REF} is chosen to be −0.021 V. The supply voltage (V_{CC}) range of MAX-9117 is 1.6–5.5 V and it is required to be the same as the bias voltage of the retrodirective array (V_{bias}). If V_{in} is larger than V_{REF}, V_{out} is expected to be V_{bias}. The specific value of each voltage will be given in the following section.

4.4 Power management performance

The proposed power management scheme consists of the rectenna and the zero-cross detector. First, the performance of the rectifier circuit is tested without the circular sector antenna. In Fig. 7, the simulated and measured rectified output voltages are plotted against input RF power. The input RF power is calculated at the point between the antenna and the rectifier circuit.

Before combining the rectenna with the zero-cross detector, the rectenna is measured in a far field test setup. The test setup is illustrated in Fig. 8. The V-band transmitter (TX) system consists of a synthesised sweeper (HP 863620A), millimeter-wave source module (HP 83557A), a power amplifier (HH PAV-1B) and a horn antenna (Dorado GH-15). The rectenna is set up at the

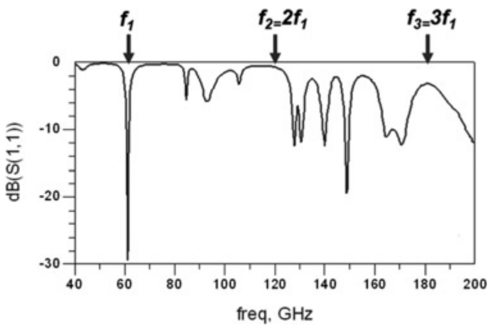

Figure 6 *Simulated return loss of the circular sector antenna suppressing second and third harmonic frequencies*

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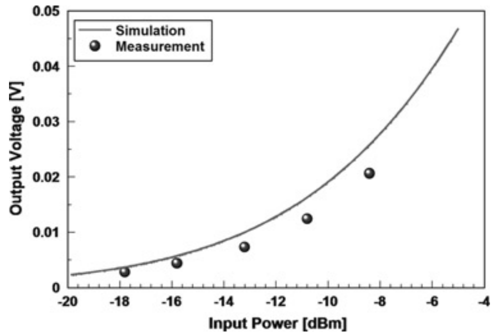

Figure 7 *Simulated and measured rectified output voltages plotted against input RF power*

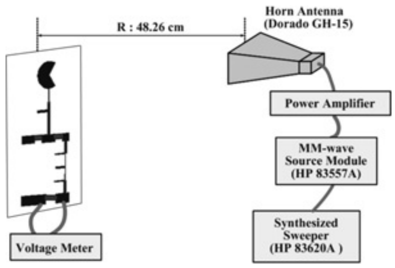

Figure 8 *Test setup to measure rectenna performance*

distance of 48.26 cm as a receiver (RX) and the rectified DC voltage is measured by a digital multimeter (HP 3435A). Fig. 9 exhibits the measured output voltage against the power density (P_D) given by

$$P_D = \frac{P_r}{A_e} = \frac{P_t \cdot G_t}{4\pi R^2} \quad (4)$$

where P_r is the received power, P_t the transmitted power, A_e an effective area, G_t the transmitting antenna gain (20 dBi), and R the distance (48.26 cm).

In order to observe the sensitivity of the proposed power management scheme, the rectenna is combined with the zero-cross detector. Therefore the load of the rectenna is connected to V_{in} of the zero-cross detector. The test setup is identical to that shown in Fig. 8 and the bias setup for

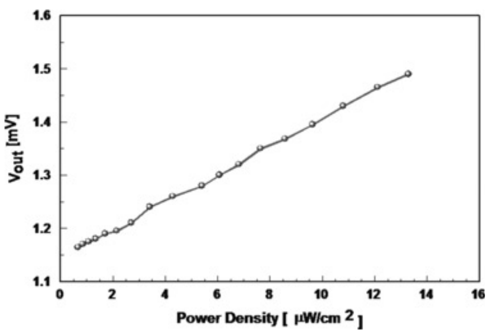

Figure 9 *Measured output voltage against the power density*

the zero-cross detector is given in Fig. 10. Assuming the bias voltage of the retrodirective array (V_{bias}) is 5 V, V_{CC} and V_{EE} are supplied with 5 and −0.58 V, respectively. In order to realise the zero reference voltage, a V_{REF} of −0.021 V is applied. Therefore V_{out} is expected to be 5 V when the power management scheme turns on. For these voltage conditions, V_{out} is measured and plotted in Fig. 11 by varying the RF power level from TX. This triggers power management scheme to start supplying a bias voltage to the retrodirective array when the RX power density is larger than 0.006 mW/cm^2.

5 System performance

The final retrodirective array system is implemented with the proposed power management scheme, as shown in Fig. 12.

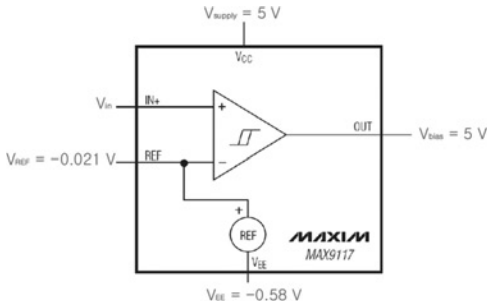

Figure 10 *Bias setup for the zero-cross detector*

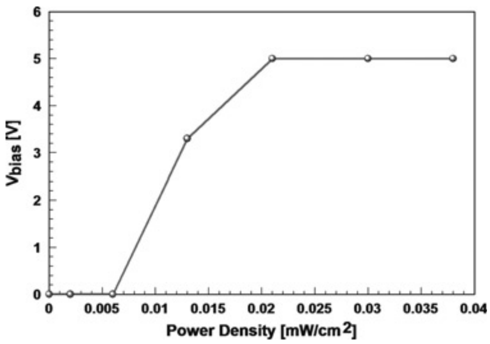

Figure 11 *Measured output voltage with the power management scheme*

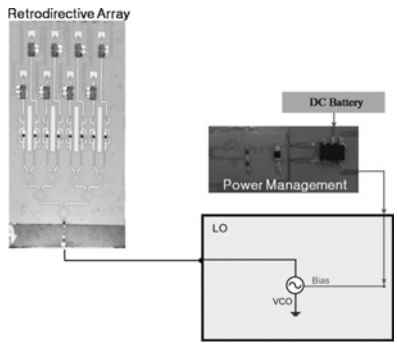

Figure 12 *Final retrodirective array system implemented with the proposed power management scheme*

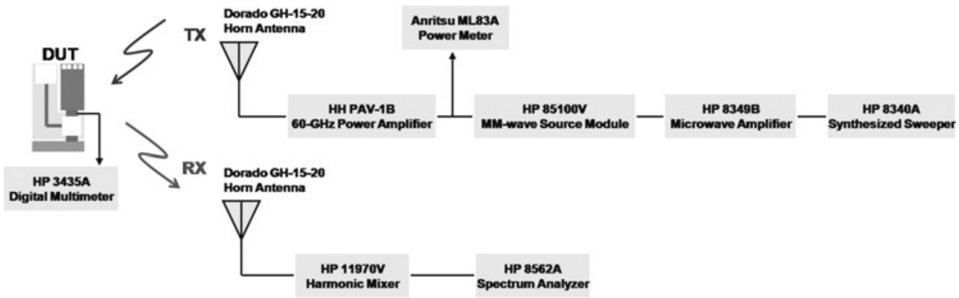

Figure 13 *Test setup to measure retrodirective array system performance*

The retrodirective array and the power management scheme are separately developed and then assembled together. In this system, an external LO is used to demonstrate the proposed concept.

The main function of the proposed system, the self-beam steering capability, is tested by measuring the bistatic radar cross-section (RCS). The test setup is depicted in Fig. 13. The TX system setup is the same as the power management test setup except that a microwave power amplifier is employed to increase the RF power transmission. The RX system consists of a horn antenna (Dorado GH-15), a down-converter (HP 11970V harmonic mixer) and a spectrum analyser (HP 8562A). The retrodirective array system is positioned at device under test (DUT) in Fig. 13.

The functionality of the power management is first tested in this test setup. When the transmitting RF power is swept, the output power is measured from the LO at the DUT. In Fig. 14, it is observed that the bias of the LO turns on when the power density $>0.013\ \text{mW/cm}^2$ and then the retrodirective array system starts working. This critical value is changed due to the load impedance change.

Finally, the bistatic RCS is measured by transmitting enough RF power to turn on the system. When the source (TX) is located at -30°, $0^\circ$and $+30^\circ$, the power at RX is measured and plotted in Fig. 15. The measured results show that the retrodirective system is working well with the proposed power management.

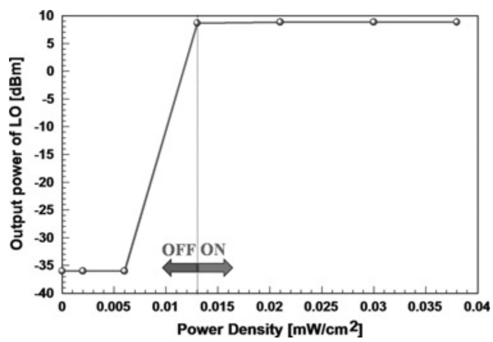

Figure 14 *Measured output power of LO in the proposed retrodirective array system*

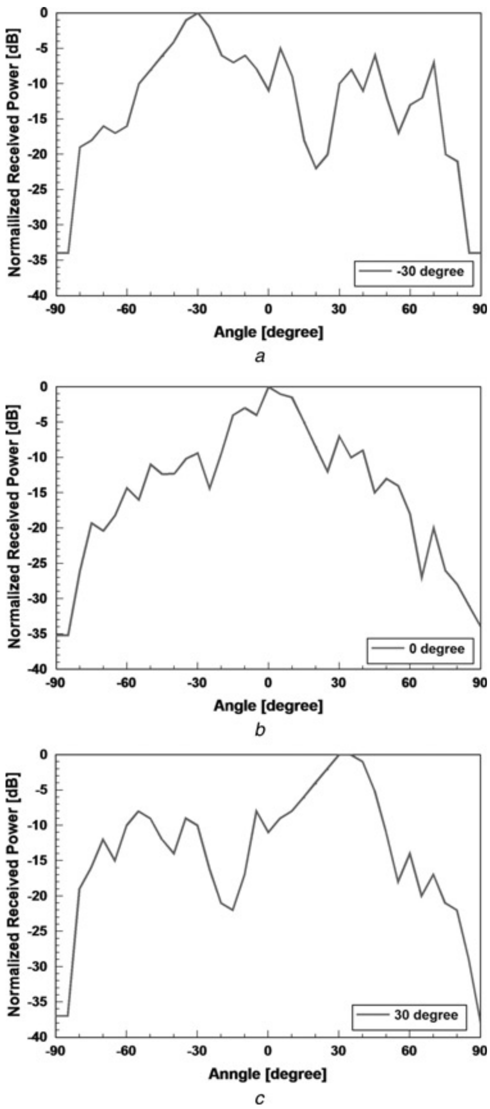

Figure 15 *Bistatic RCS measurement results at source*

a -30°
b 0°
c $+30^\circ$

6 Conclusion

A 60 GHz retrodirective array system is presented with an efficient power management. It can conserve battery power during its sleeping mode with extremely low power

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consumption and turns on only when it needs to operate. The efficient power management scheme is implemented by way of a rectenna and a zero-cross detector to control the bias of the LO. The zero-cross detector is used to enhance the sensitivity of the proposed system. The zero-cross detector can also be extended to bias the amplifiers as well. The proposed technology can be applied to MMICs for wireless multimedia sensor servers to relay wireless sensors and remote data collectors.

7 Acknowledgment

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