Surface-Wave Coupling of Active Antennas for Homodyne Sensor Systems

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***Abstract*—In this paper, we present a novel method for significantly enhancing the performance of low-cost millimeter-wave-sensor systems based on active integrated antennas. Our method uses the planar active antenna's parasitic surface-wave field as a local-oscillator signal for a mixing rectenna. Compared to a self-mixing active 67-GHz antenna, the surface-wave coupled rectenna receiver shows a considerably improved minimum detectable signal (10 dB lower) and the possibility for high-quality homodyne in-phase/quadrature signal detection.**

***Index Terms*— Active antenna, automotive radar, direction-sensitive Doppler radar, surface-wave coupling.**

I. Introduction

ACTIVE integrated antennas are considered as key elements for low-cost sensor systems [1] and communication transceivers [2]. Simple self-mixing operation is commonly proposed for signal detection [3]–[5]. In self-mixing oscillators, the active device is simultaneously used as an RF power generator and as a low-level detector. As the dc power level in the active devices is usually high, considerable f^{-1} IF noise is generated. In simple continuous wave (CW) Doppler radar systems, low-speed values correspond to low Doppler frequencies. An increased f^{-1} intermediate frequency (IF) noise level decreases the speed measurement accuracy in these systems [6]. In an FM continuous wave (FMCW) or pulse radar system, modulation of the active antenna is necessary. Modulation of an oscillator is usually disturbing the circuit's electrical and thermal equilibrium, resulting in operation point fluctuations. This effect leads to artificial video signals in self-mixing oscillators, degrading the quality of the sensors systems. One major application of active antennas are low-cost self-mixing CW Doppler radar systems. In simple self-mixing operation, the velocity of a target is related to the frequency of the Doppler signal, however, no information about the sign of the measured velocity is provided. Even in very low-cost sensor systems (traffic monitoring, automotive ground speed measurement) information about the target's direction of motion is crucial.

In this paper, we investigate a novel method for enhancing the performance of active integrated antenna significantly, overcoming the three major problems discussed above. The basic idea behind our method is to use a Schottky rectenna as a surface-wave coupled mixer. In planar millimeter-wave active antennas, considerable RF power is lost due to parasitic coupling to substrate surface waves [7]. In our transceiver concept, these surface waves are used as local oscillator (LO) signal for a mixing rectenna. The rectenna uses a Schottky diode with very low bias current (typical 0–200 μA) as mixer. The dc bias current in the Schottky diode is low, resulting in a low f^{-1} IF noise level. The rectenna is electrically insulated from the active antenna. This leads to strong decoupling between modulation and the IF signal in FMCW or pulse radar sensors. By properly choosing the distance between the active antenna and the rectenna, the LO signal applied to the rectenna exhibits a phase shift of 90° related to the signal generated in the active antenna. Thus, the IF signal generated in the active antenna by means of self-mixing operation and the IF signal generated in the mixing rectenna exhibit the same phase shift of 90°, providing a simple possibility for direction sensitive velocity measurement [8], [9].

In what follows, we compare the performance of a 67-GHz integrated self-mixing active antenna employing an IMPATT diode and a surface-wave coupled mixing rectenna. The IMPATT diode is monolithically integrated on a high-resistivity silicon substrate. The passive rectenna structure is realized on high-resistivity silicon substrate too, and a planar silicon Schottky diode is integrated by means of flip-chip technology. For various dc operation points, the minimum dectectable signal (MDS) of the surface-wave coupled rectenna is measured. Application in a direction-sensitive Doppler radar is demonstrated.

II. Surface-Wave Coupled Rectennas

A. Principle of Operation

In planar layered substrates, commonly used in modern integrated millimeter-wave circuits, various surface-wave modes $(\mathrm{TE}_n, \mathrm{TM}_n)$ might be excited [7]. Due to this fact, considerable millimeter-wave power is coupled from the circuit's structure to the surface-wave field. Surface-wave excitation might be reduced by means of electrically thin substrates $(h < 0.05\lambda_0)$, however, mechanical considerations and the loss of radiation efficiency in planar antennas lead to an optimal value of substrate thickness [7]. In this paper, we investigate a 67-GHz resonant microstrip dipole patch antenna on a 125-μm silicon substrate. For this type of active antenna [10], a numerical simulation by the method of moments showed that approximately 19% of the generated RF power are parasitically coupled to the surface-wave field, while 36% are radiated into free space and 45% are dissipated due to ohmic and dielectric losses.

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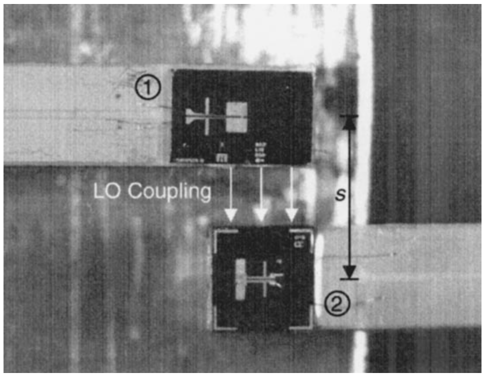


Fig. 1. Configuration of active antenna and surface-wave coupled rectenna as investigated here. The active antenna (1) is located on a fixed brass heat sink while the mixing rectenna (2) might be moved to various positions s.

A certain fraction of the RF power coupled to the surface-wave field is radiated from the edges of the substrate. This power can easily be coupled to another M^3IC located in the vicinity of the active antenna. If the surface-wave coupled M^3IC is a rectenna, the received surface-wave radiation might serve as a LO signal. Based on this principle, a surface-wave coupled homodyne sensor system might be built (see Fig. 1).

B. Basic Measurement Setup

To characterize the proposed transceiver principle, the active antenna consisting of a resonant dipole and a monolithically integrated IMPATT diode is mounted on a brass heat sink. The rectenna consists of a resonant dipole patch antenna connected to a silicon Schottky diode. Please note that the active antenna is separated from the rectenna by free space because only two separate chips were available, but integration of both the active antenna and rectenna on a single substrate is straightforward. If the active antenna and rectenna are located on the same substrate, even stronger LO coupling, resulting in increased rectenna sensitivity, is expected. An experimental advantage of using two separate chips is the possibility to change the separation s between the active antenna and rectenna by means of a micrometer translation stage. From an adjustable constant current source, a bias current $I_{0,\,\mathrm{IMPATT}} = 19 \cdots 30$ mA is applied to the IMPATT diode ($U_{0,\,\mathrm{IMPATT}} = 21.5$ V) while the rectenna's silicon Schottky diode is biased with $I_{0,\,\mathrm{Schottky}} = 0 \cdots 150$ μA. The Doppler signal obtained by the active antenna in self-mixing operation is fed into a low-noise amplifier (LNA) with an input impedance of 200 Ω ($\approx$ small-signal resistivity of the IMPATT diode) and a gain of +47 dB. The Doppler signal of the rectenna is amplified by a similar LNA with 2-kΩ input impedance and +47-dB video gain. Both video amplifiers have an equal bandwidth of 20 kHz, resembling the frequency range appearing in typical automotive CW Doppler radar applications. For the desired LNA input impedance of 200 Ω and 2 kΩ, respectively, the noise contribution of the LNA's to the total video noise of the IMPATT and Schottky diode could be neglected.

The video signals of both the active antenna and rectenna are fed into a digital storage scope, capable of measuring the signals' amplitude and differential phase. To measure the video noise levels generated by both receivers, a root mean square (rms) voltage meter ($\mathrm{BW} = 20$ kHz) can be alternatively connected to the video outputs.

C. MDS Measurement and Determination of Maximum Radar Range

To measure the MDS of an active integrated antenna, two basic methods have been established. The method proposed in [11] uses a synthesizer radiating an RF signal of precisely known power on the active antenna under test. From the amplitude of the resulting IF signal, the isotropic conversion loss L_{ISO} is deduced. By additionally measuring the IF noise level of the active antenna, the MDS can be calculated. As our sensor concept is mainly intended to be used in CW Doppler radar systems, the expected IF frequencies are between 10 Hz and 500 kHz. For these low IF frequencies, the MDS measurement method described above is not practical since locking and frequency-pulling effects take place if the externally radiated RF signal has a frequency within or near the locking frequency range of the active antenna.

Another commonly used method to measure the MDS of an active antenna is proposed in [12]. In this concept, the radiation from the active antenna is coupled to a hollow waveguide setup by means of a standard gain horn. In the waveguide setup, a short is virtually shifted in position periodically by switching a p-i-n diode. The virtual motion of the short is resulting in a phase shift of the reflected signal. This reflected signal is radiated from the standard-gain horn again and is finally received by the active antenna. As the received signal is periodically phase shifted, an ac IF signal can be detected. From the attenuation parameters of the waveguide setup and the distance between the active antenna and the standard-gain horn, the received power P_R can easily be deduced. By comparing the IF signal and IF noise level of the active antenna, the MDS is calculated. As we had no p-i-n switch available for the frequency of the transceiver (65–76 GHz), we chose another method.

We mainly intended to compare the performance of an active antenna in self-mixing operation with a mixing surface-wave coupled rectenna qualitatively. As a low-cost alternative to the MDS measurement methods discussed above, a simple MDS measurement method has been developed. We chose to use a bras trihedral reflector being moved by a small motor $\Delta r = 10$ mm back and forth as a radar target. The radar cross section σ_s of the trihedral reflector was determined using a network analyzer and a standard gain horn. Furthermore, we compared the measured radar cross section with theoretical values calculated from the geometry of the reflector. From previous measurements, the equivalent isotropic radiated RF power equivalent isotropic radiated RF power (EIRP) of the active antenna was known as a function of IMPATT bias current. The gain G_A of the planar active antenna was calculated using a method-of-moments simulation. The received signal power P_R returning from the radar target located in a distance r_0 and being coupled to the active device is

$$P_R = \mathrm{EIRP} \cdot G_A \frac{\sigma_S \lambda_0^2}{(4\pi)^3} \cdot \frac{1}{r_0^4}. \qquad (1)$$

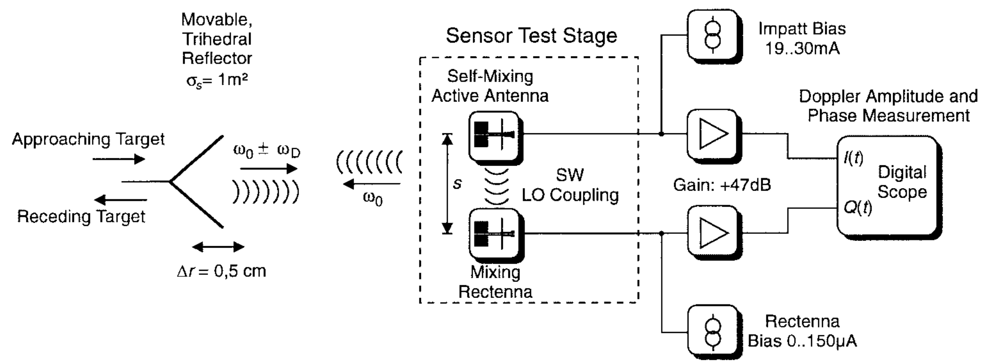


Fig. 2. Basic measurement setup used to characterize the surface-wave coupled rectenna transceiver.

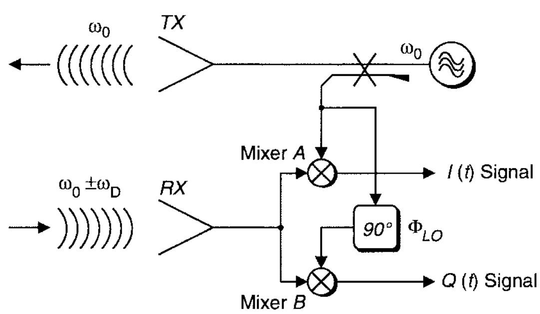


Fig. 3. Operation principle of classic direction-sensitive CW Doppler radar.

With no target present, the IF noise voltage U_N at the terminals of the active antenna was measured for a bandwidth of 20 kHz (10 Hz–20 kHz, integration time $\tau = 1.0$ s), which is a typical value for CW Doppler radar systems. With the moving target present, an IF voltage U_{IF} can be measured. The sensitivity S_V of the receiver is defined as

$$S_V = \frac{U_{\text{IF}}}{P_E} \cdot \frac{\lambda_0^2 G_A}{4\pi}. \tag{2}$$

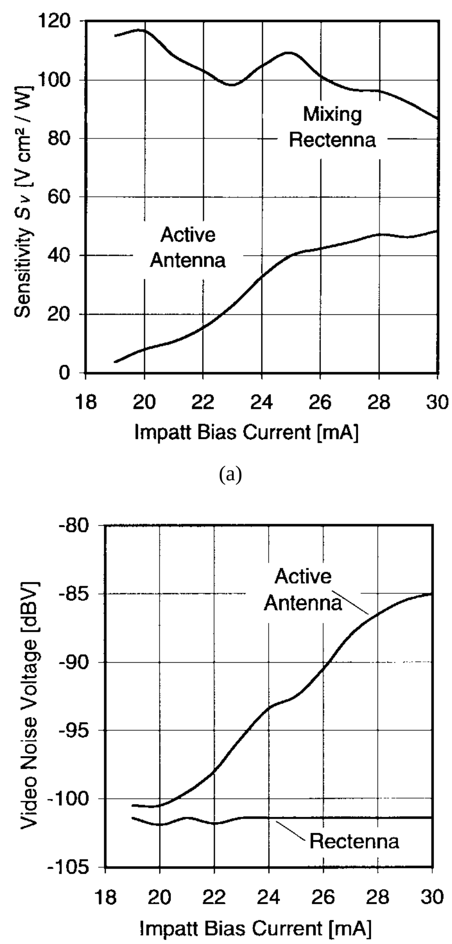
The MDS is defined as +3 dB above the noise floor of the receiver [11]. If the MDS is present at the receiver input, the IF voltage is raised by a factor of $\sqrt{2}$ (+3 dB). From (2), an expression for the MDS can easily be deduced as

$$\frac{U_{\text{IF}}}{P_E} \text{MDS} = \sqrt{2}\, U_N \tag{3}$$

$$\text{MDS} = \sqrt{2}\, \frac{U_N}{U_{\text{IF}}} \cdot P_E. \tag{4}$$

The MDS depends on the bias current of the active antenna. An increment of the bias current leads to higher RF output power (larger radar range), but also produces an increased IF noise level (higher MDS). Furthermore, conversion gain of the self-oscillating mixer is strongly depending on the bias current of the IMPATT diode. Due to these facts, the MDS was not found to be a helpful characteristic for a complete description of the sensor. The maximum radar range r_{MAX}, hence, the distance in which a target of radar cross section σ_s has to be located to produce a return signal equal to the MDS of the sensor is

$$r_{\text{MAX}} = \sqrt[4]{\frac{\sigma_S \lambda_0^2 G_A}{(4\pi)^3} \cdot \frac{\text{EIRP}}{\text{MDS}}} \tag{5}$$



(a)

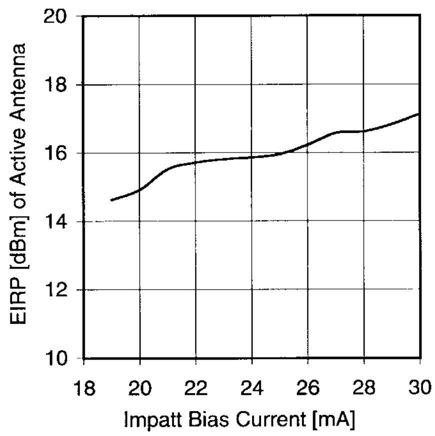
(b)

Fig. 4. (a) Measured sensitivity S_v of active antenna and mixing rectenna. (b) Measured rms video noise voltage U_N of active antenna and mixing rectenna for a 20-kHz video bandwidth (10 Hz–20 kHz) and an integration time $\tau = 1.0$ s.

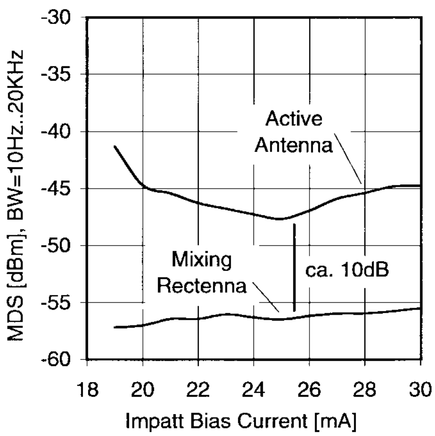
Since the maximum obtainable radar range r_{MAX} can serve as an additional figure-of-merit of the sensor, we also compared the maximum radar ranges obtainable with a self-oscillating self-mixing active antenna with the results of a surface-wave coupled rectenna.

D. Measurement of I/Q Receiver Properties

As the rectenna might be moved to various positions s, the phase of the LO signal coupled from the active antenna to the



(a)



(b)

Fig. 5. (a) Measure EIRP of the active antenna. (b) Measured MDS of active antenna and mixing rectenna for a 20-kHz bandwidth (BW $=10$ Hz–20 kHz).

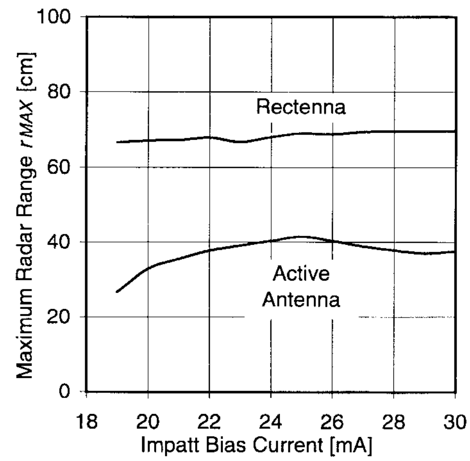


Fig. 6. Calculated maximum radar range $5_{\max}$ as defined in (5) for a target of $\sigma_s = 1$ m^2 radar cross section.

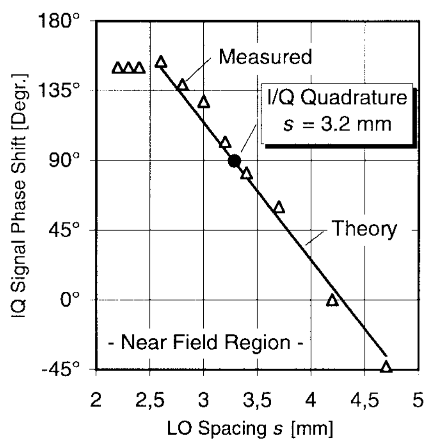


Fig. 7. Phase shift between active antenna's and rectenna's video signal as function of distance s between active antenna and rectenna. The small triangles represent measured values, while the solid line shows theoretical results calculated from (10).

rectenna can be adjusted. If the phase of the LO signal Φ_{LO} is tuned to Φ_{IQ}

$$\Phi_{\text{LO}} \stackrel{!}{=} \Phi_{\text{IQ}} = \left(\tfrac{1}{2} + n\right) \cdot 180^\circ, \qquad n \in \{0, \pm 1, \pm 2, \cdots\} \tag{6}$$

a simple in-phase/quadrature (I/Q) receiver system can be build. One very attractive application of I/Q receiver systems is their use in direction-sensitive Doppler radar. The classic principle of direction-sensitive Doppler radar is shown in Fig. 3 [8], [9]. For an LO phase shift of exactly 90°, the associated Doppler signals $I(t)$ and $Q(t)$ for a Doppler frequency $+\omega_D$ (approaching target) are

$$I(t) = I_0 \cdot \cos \omega_D t \tag{7}$$

$$Q(t) = -\, Q_0 \cdot \sin \omega_D t. \tag{8}$$

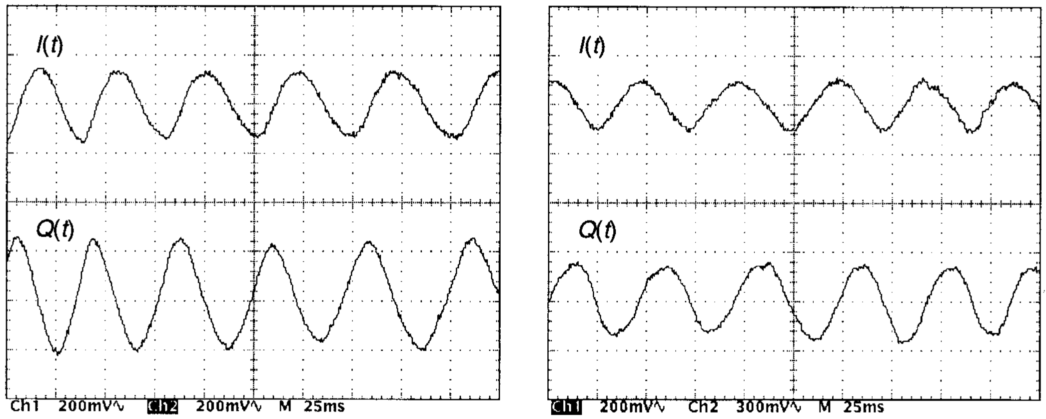
From the phase relationship between I and Q signal, the sign of ω_D can easily be deduced. Theoretically, the free-space LO signal (wavelength: λ_0) phase shift, seen by a rectenna located in a distance s from the active antenna is

$$\Phi_{\text{LO}} = \Phi_0 + 360^\circ \cdot \frac{s}{\lambda_0}. \tag{9}$$

The phase correction Φ_0 takes into account the displacement between the phase center and the geometrical center of the antenna due to reactive near-field effects in the vicinity of the active antenna. For free-space radiation coupling,

$$s_{\text{IQ}} = s_0 + \left(\frac{1}{2} + n\right) \cdot \frac{\lambda_o}{2}, \qquad n \in \{0, 1, 2, \cdots\} \tag{10}$$

has to be chosen. In the work reported in this paper, the active antenna is separated from the rectenna by free space because a two-chip configuration was chosen to increase the flexibility of the experimental setup. However, integration of both the active antenna and rectenna on a single substrate is straightforward. In our case, (9) holds exactly. If the rectenna and the active antenna are located on the same substrate, the wavelength of the fundamental surface-wave mode λ_s has to be inserted instead of λ_0. For a backside metalized substrate, the TM_0 mode is the fundamental surface-wave mode. For active integrated dipole antennas, the substrate has to be electrically thin ($h/\lambda_0 < 0.05$) to reduce losses due to excessive surface-wave excitation. In this case, we can assume $\lambda_s \approx \lambda_0$. As the two wavelengths are almost equal in both cases, the results from the free-space experiments reported in this paper may easily be adopted for a fully integrated front-end, where the active antenna and rectenna are located on the same substrate. In (10), a periodical nature of s_{IQ} is shown.



(a) (b)

Fig. 8. (a) Measured video signal of active antenna (I) and rectenna (Q) for approaching target. (b) Measured video signal of active antenna (I) and rectenna (Q) for receding target.

However, for optimal detection, the LO signal coupled to the rectenna should be as strong as possible. In practice, $n = 0$ or $n = 1$ are chosen. If the active antenna and rectenna are located on the same substrate, even a stronger LO coupling, resulting in increased rectenna sensitivity, is expected.

III. Measured Results

We first measured the sensitivity of the active antenna and the mixing rectenna for various dc operation points of the active antenna. To achieve maximum LO coupling, the minimum value $s = 2.1$ mm was chosen, i.e., the end faces of the two substrates touched. As can be seen in Fig. 4(a), the sensitivity S_V of the mixing rectenna is significantly higher than that of the active antenna and varies only slightly with the LO power. This fact implies that the LO power actually coupled to the rectenna reached the compression level of the mixer. Fig. 4(b) shows the rms video noise voltage of both the active antenna and mixing rectenna for a typical video bandwidth of 20 kHz (10 Hz–20 kHz). As expected, the noise voltage of the active antenna increases with increasing bias current, while the noise voltage of the rectenna (150-μA bias) stays almost constant. The EIRP of the active antenna varies between $+15$ to $+17$ dBm for typical IMPATT bias currents. We calculated the MDS of the active antenna for a 20-kHz video bandwidth. For the surface-wave coupled mixing rectenna receiver proposed in this paper, an MDS of -57 dBm for the IF band from 10 Hz to 20 kHz has been obtained.

As shown in Fig. 5(b), the MDS of the mixing rectenna is at least 10 dB better then the MDS of the active antenna in the self-mixing mode. This is because the rectenna exhibits a greater sensitivity and lower video noise level. From the enhanced MDS of the mixing rectenna, an estimate for the radar-range increment can be deduced. The maximum radar range r_{MAX}, as defined in (5), has been calculated as a function of IMPATT bias current for both the active antenna and mixing rectenna. As shown in Fig. 6, the maximum radar range of the sensor system is extended by 78% if the MDS is 10 dB lower.

To prove that homodyne I/Q detection would be possible with the new sensor concept, we measured the phase shift between the video signals of the active antenna and rectenna for various distances s between the active antenna and rectenna (see Fig. 7). For small coupling distances ($s < 2.5$ mm), the linear phase relationship does not hold true due to reactive near-field coupling. This leads to the deviations between measured and calculated phase shifts for small s in Fig. 7. In terms of (9) and (10), the near-field phase center correction ϕ_0 was calculated to be +20° ($s_0 = 0.2$ mm). For exact I/Q detection, $s_{\mathrm{IQ}} = 3.2$ mm was chosen ($n = 1$). With this separation, we recorded the video signals of both the active antenna and mixing rectenna by means of a digital storage scope [see Fig. 8(a) and (b)].

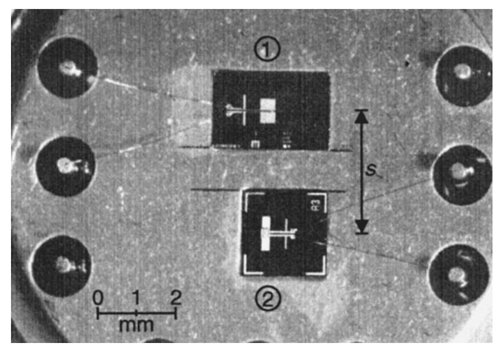


Fig. 9. Photograph of a direction-sensitive 76-GHz Doppler radar front-end based on an active antenna (1) and a surface-wave coupled rectenna (2).

In Fig. 8(a) (approaching target), the phase difference between the active antenna's and rectenna's video signal is −90°, while in Fig. 8(b) (receding target), the phase difference is +90°.

In low-cost applications (e.g., motion control, counting of persons), the significant phase difference can be detected by means of a commercially available phase comparator integrated circuit (IC), however, digital signal processing might be chosen in more complex purposes such as collision-avoidance or ground-speed measurement.

Direction-sensitive Doppler radar front-ends built by means of surface-wave coupled active antennas might find interesting applications [13] in modern intelligent transportation systems (ITS's). For this purpose, we assembled an active 76-GHz antenna and a surface-wave coupled rectenna on a TO8 header [14] (see Fig. 9). A characterization of the front-end showed that the simple and low-cost device provided reliable and accurate direction-sensitive velocity information.

IV. Conclusion

In planar active millimeter-wave antennas, considerable RF power is coupled to surface waves. In this paper, we propose the use of these surface-waves as an LO signal feed for a mixing rectenna. As measured results showed, the MDS of the surface-wave coupled mixing rectenna is at least 10 dB lower than that of the active antenna, resulting in a 78% increased maximum radar range.

We showed that simple direction-sensitive CW Doppler radar sensors can be built by properly adjusting the position of the rectenna with respect to the active antenna. The novel concept can be applied to monolithically integrated design as well as to two-chip configurations.

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