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 sensors systems based on active integrated antennas. Our method uses the planar active antenna's parasitic surface–wave field as LO signal for a mixing rectenna. Compared to a self–mixing active 67 GHz antenna, the surface–wave coupled rectenna receiver shows a considerably improved MDS (10dB lower) and the possibility for high quality homodyne I/Q signal detection.

INTRODUCTION

Active integrated antennas are considered as key elements for low cost sensor systems and communication transceivers. Commonly, simple self–mixing operation is proposed for signal detection [1,2]. In self–mixing oscillators the active device is used as RF power generator and as low–level detector simultaneously. As the DC power level in the active devices is usually high, considerable f^{-1}–IF noise is generated. In simple CW Doppler radar systems, low speed values correspond to low Doppler frequencies. An increased f^{-1} – IF noise level decreases the speed measurement accuracy in these systems [3]. In a 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 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, whether the target is approaching or receding, 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 coupling to substrate surface–waves [4]. In our transceiver concept, these parasitic surface–waves are used as 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 diode is low resulting in low f^{-1}–IF noise level. The rectenna is electrically insulated from the active antenna. This leads to a strong decoupling between modulation– and 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 degrees 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 degrees providing a simple possibility for direction sensitive velocity measurement [5].

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 [6]. 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 MDS of the surface–wave coupled rectenna is measured.

SURFACE–WAVE COUPLED RECTENNAS

Modern integrated millimeter wave circuits are commonly built on planar layered substrates. In the described substrate configuration, various surface–wave modes (TE_n , TM_n) might be excited [4]. Due to this fact, considerable millimeter wave power is coupled from the circuit's structure to the surface–wave field, leading to power loss, parasitic resonance and parasitic coupling. Surface–wave excitation might be reduced by means of electrically thin substrates (h < 0.05 λ_0), however mechanical considerations and the loss of radiation efficiency in planar antennas lead to an optimal value of substrate thickness [4]. In this paper, we investigate a 67 GHz resonant microstrip dipole patch antenna on a 125µm silicon substrate. As active element, a monolithically integrated Impatt diode is used [6]. For this active antenna, 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. Figure 1 shows a photograph of a surface–wave coupled transceiver. To characterize the transceiver, the active antenna, consisting of a resonant dipole and an 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 the rectenna on a single substrate is straightforward.

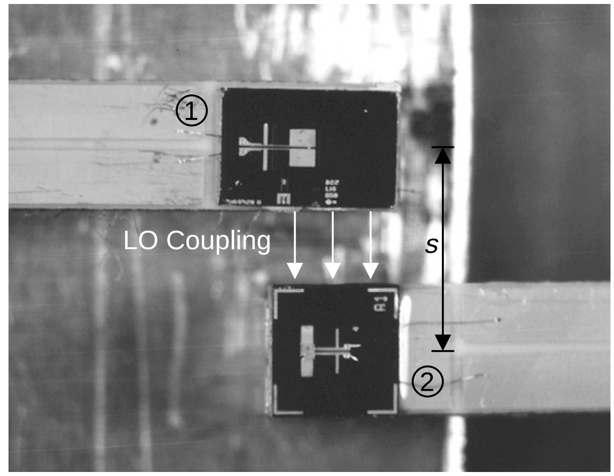

Figure 1: Configuration of active antenna and surface–wave coupled rectenna as investigated in this paper. The active antenna (1) is located on a fixed bras heatsink while the mixing rectenna (2) might be moved to various positions s.

If active antenna and rectenna are located on the same substrate, even a 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 the rectenna by means of a micrometer translation stage. From an adjustable constant current source, a bias current $I_{0,\text{Impatt}}$ = 19..30 mA is applied to the Impatt diode ($U_{0,\text{Impatt}}$ = 21.5V) while the rectenna's silicon Schottky diode is biased with $I_{0,\text{Schottky}}$ = 0..150 µA. In a distance r_0 = 12cm, a trihedral reflector with a bore–side radar cross–section of $\sigma = 1\text{m}^2$ is located (Figure 2). By means of a small motor, the reflector is constantly moved $\Delta r = \pm 0{,}5$cm back and forth. The Doppler signal obtained by the active antenna in self mixing operation is fed into a LNA with an input impedance of 200Ω (≈ small signal resistivity of the Impatt diode) and a gain of +47dB. The Doppler signal of the rectenna is amplified by a similar LNA with 2KΩ input impedance and +47dB video gain. Both video amplifiers have an equal bandwidth of 20KHz, resembling the frequency range appearing in typical automotive CW Doppler radar applications.

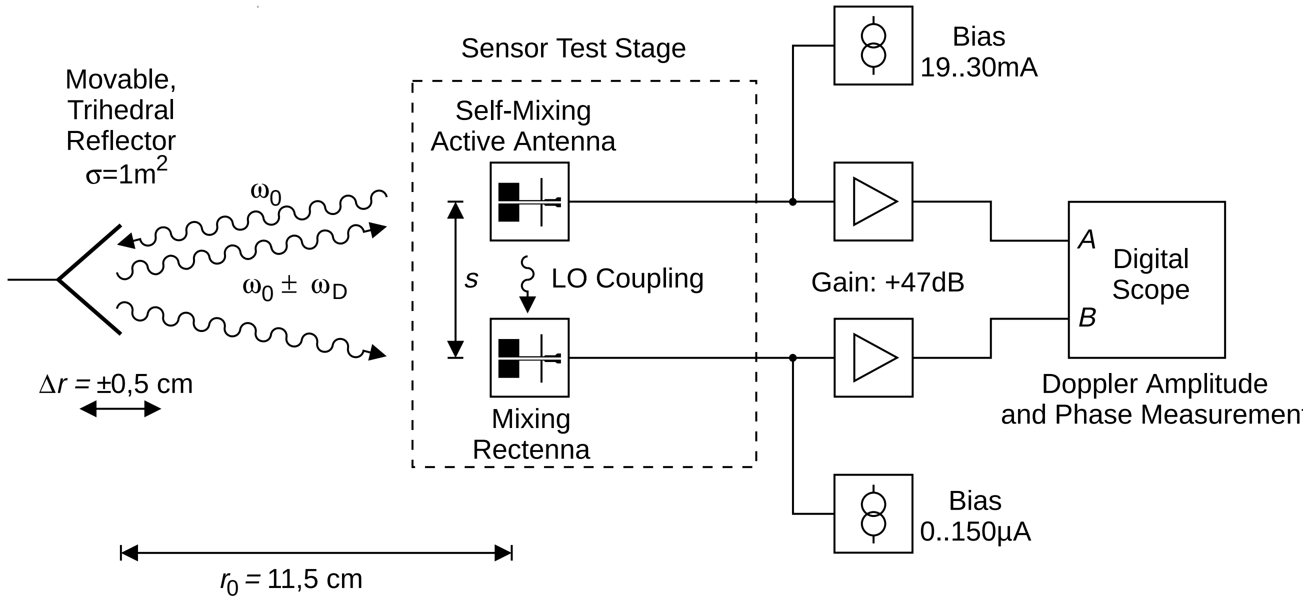

Figure 2: Basic measurement setup used to characterize the surface–wave coupled rectenna transceiver.

The video signals of active antenna and rectenna are fed into a digital storage scope, capable to measure the signals' amplitude and differential phase. To measure the video noise levels generated by both receivers, a RMS voltage meter ($BW = 20$KHz) can be alternatively connected to the video outputs.

MEASURED RESULTS

We first measured the sensitivity of the self–mixing 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 Figure 3, the sensitivity 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. Figure 4 shows the RMS video noise voltage of both active antenna and mixing rectenna for a typical video bandwidth of 20KHz. As expected, the noise voltage of the active antenna increases with increasing bias current while the noise voltage of the rectenna (150µA bias) stays almost constant. The equivalent isotropic radiated RF power (EIRP) of the active antenna varies between 15 dBm and 17 dBm for typical IMPATT bias currents.

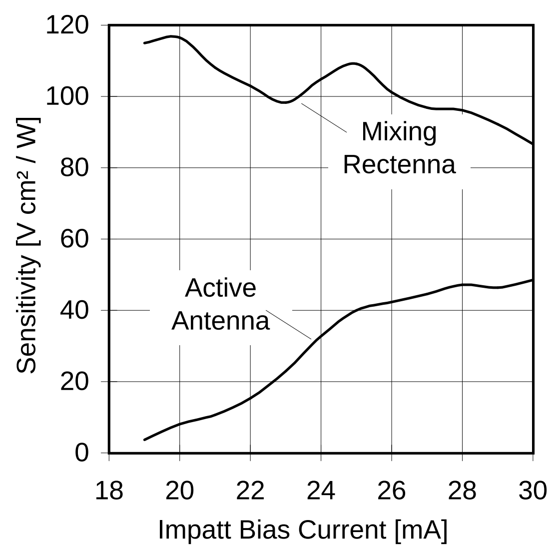

Figure 3: Measured sensitivity of active antenna and mixing rectenna.

We calculated the minimal detectable signal (MDS) of the active antenna and the rectenna as defined in [7] for a 20KHz video bandwidth. For the surface–wave coupled mixing rectenna receiver proposed in this paper, an MDS of –57dBm for the IF band from 10 Hz to 20 kHz has been obtained. As Figure 5 shows, the MDS of the mixing rectenna is at least 10dB better then the MDS of the active antenna in self–mixing mode.

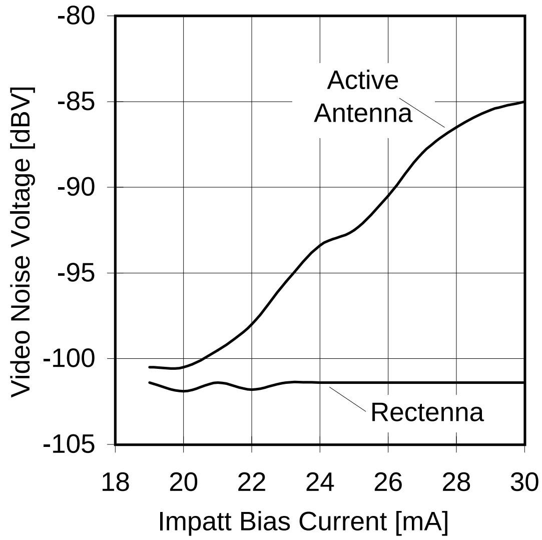

Figure 4: Measured RMS video noise voltage of active antenna and mixing rectenna for a 20kHz Video Bandwidth (10Hz...20kHz).

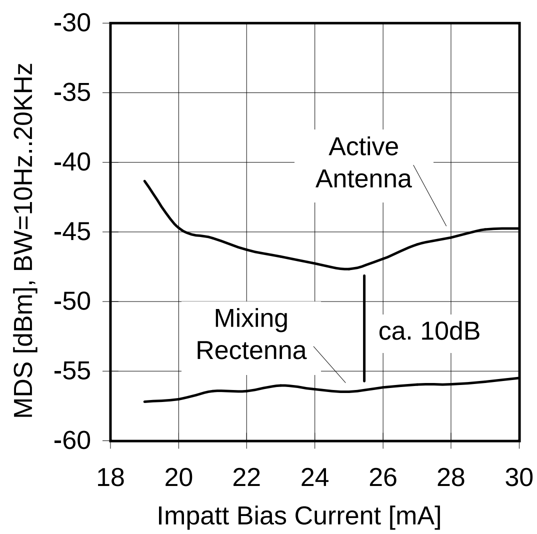

Figure 5: Measured MDS of active antenna and mixing rectenna for a 20 kHz bandwidth (*BW*=10 Hz ...20 kHz).

This is because the rectenna exhibits a greater sensitivity and a lower video noise level. From the enhanced MDS of the mixing rectenna, an estimate for the radar range increment can be deduced. As the power received from a radar target is proportional to r^{-4}, the maximum radar range of the sensor system is extended by 78%, if the MDS is 10dB lower.

CONCLUSION

In this paper, we propose the use of surface–wave radiation from planar millimeter wave oscillators as LO signal for mixing rectennas. As measured results showed, the minimal detectable signal (MDS) of the surface–wave coupled, mixing rectenna is at least 10 dB lower than that of the self–mixing active antenna, resulting in a 78% increased maximum radar range. The novel concept can be applied to monolithically integrated design as well as to two chip configurations. Further more, proper adjustment of active antenna and rectenna provides a simple possibility for homodyne *I*/*Q* signal detection [5].

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