A 77GHz Monolithic IMPATT Transmitter in Standard CMOS Technology

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Abstract — **In this paper, a fully integrated transmitter at 77GHz is presented in a 0.18μm standard CMOS technology. The system consists of a lateral IMPATT diode and a microstrip patch antenna. The antenna impedance seen by the IMPATT diode is optimized using the high frequency electromagnetic (EM) field solver, Sonnet, which is matched to the measured impedance of the diode. The transmitted power had an offset frequency of -0.13% from the simulation results.**

Index Terms — **CMOS, IMPATT diode, microstrip patch antenna, stub, Sonnet, vector network analyzer .**

I. INTRODUCTION

Monolithic millimeter-wave integrated transmitters are the key elements of sensor systems in automotive applications [1]. Their small size and light weight are advantageous in these systems when compared with the current waveguide-based solutions. So far, monolithic millimeter-wave IMPATT oscillators have been fabricated on GaAs [2], InP [3], Si [4], and SiGe [1] processes. A CMOS transmitter at 77GHz is particularly appealing from a cost reduction and system integration standpoint. In this work, for the first time, we have designed and demonstrated an integrated transmitter system at 77GHz fabricated in a 0.18μm standard CMOS technology.

One of the proposed structures for an integrated transmitter consists of an IMPact Avalanche Transit Time (IMPATT) diode [5] connected to an integrated resonant structure. To minimize the required chip area in this work, the resonator is designed to also act as the transmitting antenna. In such a topology, parasitic losses are significantly reduced, since no microstrip line is necessary to connect the oscillator to the antenna. However, the challenge then turns out to be the matching of the IMPATT diode to the antenna. This is particularly difficult in millimeter-wave frequencies and requires careful optimization of the diode structure, geometry, and antenna layout in view of the properties of the materials present in the fabrication process.

In this study, the antenna impedance seen by the IMPATT diode was estimated by the EM field solver Sonnet, while the impedance of the IMPATT diodes was characterized by on-wafer measurements of IMPATT diodes in standard CMOS processes [5]. In section II of this paper, we provide the design process of the 77GHz transmitter, followed by the experimental results of the system in section III.

II. DESIGN

A. IMPATT Diode

The cross section of the lateral IMPATT diode fabricated in a 0.18μm CMOS technology is shown in Fig. 1. The diode has a single drift region. The p^+, n, and n^+ regions of the IMPATT diode are implemented using standard source/drain, *n*-well, and ohmic contact diffusion regions respectively. The impedance of the diodes is measured up to 110GHz by means of vector network analyzer (VNA) connected to CASCADE wafer prober. To minimize the influence of the measurement setup on the diodes, a constant leveled VNA output power of -20dBm is used. The Smith chart in Fig.2 provides the reflection coefficient prior to de-embedding. At specific frequencies, it becomes greater than one, which indicates that the reflected power gets larger than the input power. Fig. 3 illustrates the measured impedance of this structure in the 76-78 GHz range.

B. Microstrip Patch Antenna

At 77GHz the IMPATT diodes can be used as active elements using standard CMOS technology [5]. However, to create oscillation they typically demand a resonator resistance below 20Ω, while the reactive part of the antenna impedance is cancelled by the one of the diode [6].

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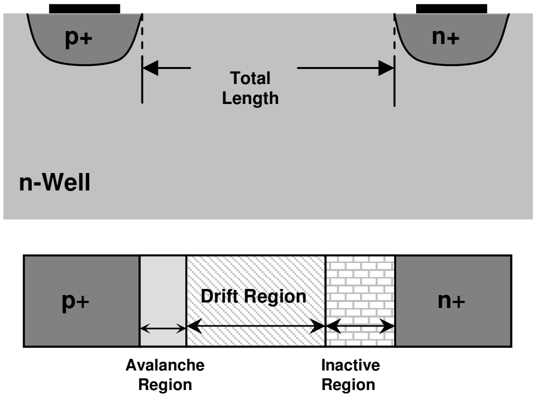

Fig. 1. Lateral IMPATT diode structure, showing the avalanche region, drift region and the inactive region.

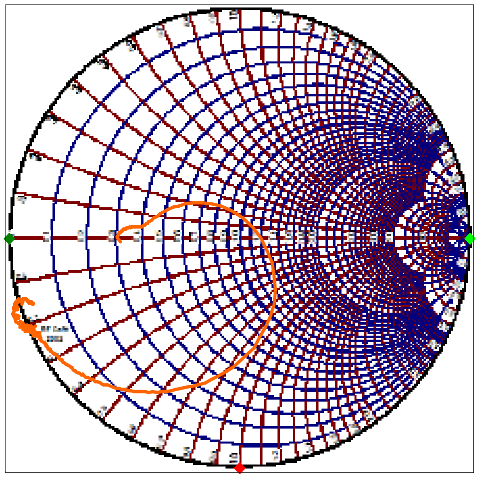

Fig. 2. Measured reflection coefficient of an IMPATT diode at V_{bias} =11V and I_{diode} =30mA prior to de-embedding.

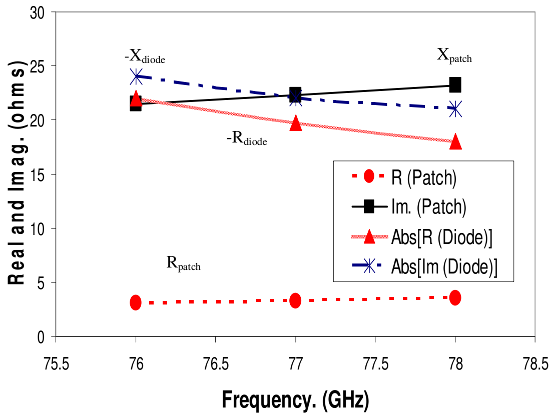

Fig.3. The real and imaginary part of the Impedance of the IMPATT diode and the microstrip patch antenna.

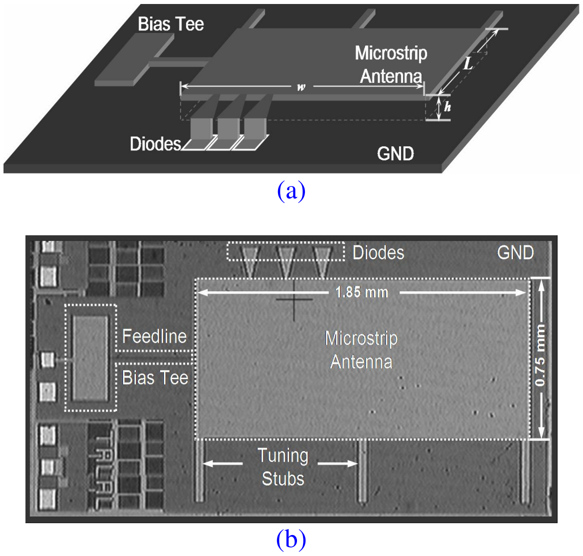

Fig. 4. Monolithic IMPATT transmitter in standard CMOS technology. (a) Layout of the integrated transmitter. (b) Die photo.

The impedance seen by the IMPATT diode was calculated using Sonnet which includes the typical relevant losses at 77GHz such as, dielectric, ohmic, radiation, and surface waves. The simulation results provided the characteristics of the antenna in the form of input impedance, gain, radiation pattern, and radiation efficiency.

By examining various Layout structures, a 750µm x 1850µm microstrip patch antenna (Fig.4) was found to match the impedance requirements of the IMPATT diode best. The calculated input impedance of the microsrtip patch antenna seen by the IMPATT diode versus frequency is depicted in Fig. 3. Since matching is obtained when $Z_{\text{diode}} + Z_{\text{antenna}} = 0$, the intersection between the negative reactance of the IMPATT diode and of the microstrip patch antenna determines the oscillation frequency. Using simulations and measurements, the load quality factor Q, is determined to be approximately 7 in this structure.

The simulated directive gain is 11dB as shown in Fig. 5 with a 4µm dielectric thickness for the patch antenna. This clearly shows the necessity of some form of beam shaping for practical applications. Major factors were taking into consideration while simulating the antenna. To name a few, we can mention feed point location, effects of the dielectric cover (passivation layer), finite size ground plane, and the substrate doping profile of the CMOS technology used. Furthermore, 3 stubs where added in the design (Fig.4). Each is 50µm x 300µm and connected to one of the radiating edges of the antenna to provide mechanical tuning. We expect all together a tuning range of 20% and 3% for the real and imaginary part of the input impedance, respectively.

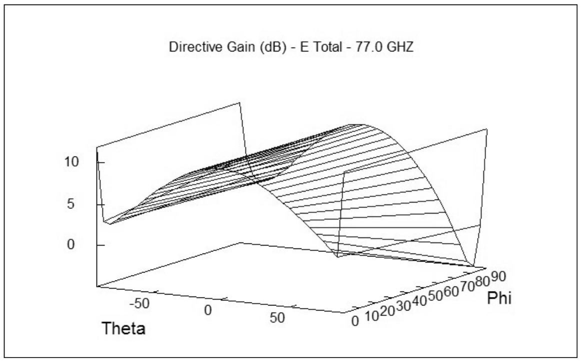

Fig. 5. The simulated directive gain of the CMOS microstrip patch antenna.

To provide multiple designs, 3 identical diodes (100µm x 0.45µm) were placed in the layout, each feeding the antenna at different locations. Diodes can be tested individually by isolating the other two using a laser trimmer. This provided higher probability in finding the perfect matching location.

The parasitics introduced by the vias and the metal layers (five layer in this process) connecting the IMPATT diode to the antenna were modeled and simulated. The results revealed a degradation of the IMPATT real and imaginary part by 25% and 5% respectively. Because of the loading effects of the depletion layer capacitances of the diode structure, the length of the antenna is shorter than an equivalent resonator operating at the same frequency. A DC bias, which is well isolated from RF, is created by utilizing a quarter wavelength high impedance microstrip line. One end is attached to the low impedance point at the non-radiating edge of the patch antenna, minimizing the disturbance of the electromagnetic fields. The other end is terminated to a low impedance pad, realized by a metal-to-metal capacitance structure of approximately 5pf.

III. MEASUREMENTS AND RESULTS

During the operation of the monolithic integrated transmitter, IMPATT diode is driven above its breakdown voltages [7], [8]. At this condition, the diode converts the DC power into RF power, and subsequently the patch radiates the power into free space. The oscillation frequency has been measured at Anritsu corporation, Morgan Hill, CA, using the setup shown in Fig. 6, which includes Anritsu ME7220A Radar Test System (RTS), WR12 E-band horn Antenna, and Anritsu MS2663C 9K-8.1GHz spectrum analyzer. The frequency band of the transmitter is initially down-converted by the RTS from 76-77GHz to the IF band of 4.7 to 5.7GHz before the radiated signal is characterized.

When the on-chip transmitter is biased at 11V, with a quiescent current of 30mA, signal is detected with an oscillation frequency of 76GHz as shown in Fig. 7. This oscillation frequency deviates about 0.13% from the predicted 77GHz. Based on the measured radiated power and the system losses, the calculated diode efficiency is -41 dB. This low efficiency is possibly a result of high capacitive loading of the depletion region. In addition, other sources of loss like the antenna surface roughness are not included in our simulations. They can in practice further increase the antenna total losses, resulting in a higher actual IMPATT efficiency. In table I, the calculated and measured radiated power levels are shown.

IV. CONCLUSION

By exploiting the lateral IMPATT diodes and the resonant characteristics of an integrated microstrip patch antenna, a self-radiating oscillator at 77GHz has been fabricated and tested for the first time in a standard CMOS technology. By using this particular configuration, area requirements and parasitic losses of the integrated transmitter are reduced to a minimum. Because of the cost-efficiency and robustness of standard CMOS manufacturing, this kind of monolithic integrated transmitter is well suited for use in millimeter-wave systems for various applications ranging from communications to automobile anti-collision radar system.

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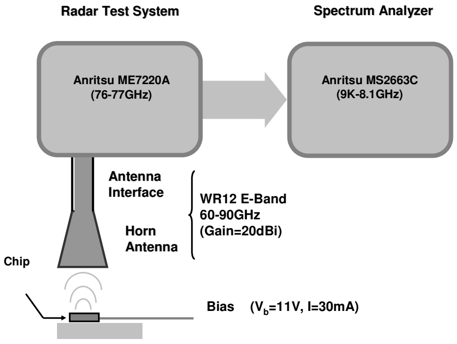

Fig. 6. Measurement setup, which includes Anritsu ME7220A Radar Test System (RTS), WR12 E-band horn Antenna, and Anritsu MS2663C 9K-8.1GHz spectrum analyzer.

TABLE I
Power calculated and measured

DC power delivered to the transmitter	330mW (25dBm)
DC losses including: - feed line resistance - resistance of the diode inactive region	2dB
Power delivered to the IMPATT diode	200mW (23dBm)
Losses of the microstrip patch antenna including: - dielectric losses - conduction losses - radiation losses	34dB
Losses of the measurement setup (from the horn antenna to the spectrum analyzer)	10dB
Measured power transmitted	-62dBm
Calculated power generated by the diode	-18dBm
Calculated diode efficiency	-41dB

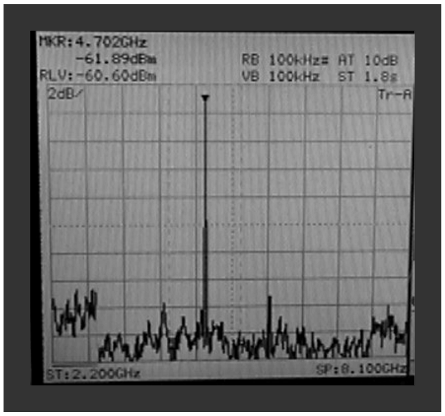

Fig. 7. Measured signal transmitted at 76GHz (IF 4.7GHz).

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