MMW FM-CW Ground-based SAR

J. Abril [(1)], E. Nova [(1)], A. Broquetas[(1)], A. Aguasca[(1)], J. Romeu[(1)], L. Jofre[(1)],
B. Mencía[(2)], J.Grajal[(2)], J. P. Pascual[(3)], T. Fernández[(3)], A. Tazón[(3)]
[(1)] *Universitat Politècnica de Catalunya,* [(2)] *Universidad Politécnica de Madrid,* [(3)] *Universidad de Cantabria*
jordi.abril@tsc.upc.edu, *jesus@gmr.ssr.upm.es*, *antonio.tazon@unican.es*

***Abstract*- This paper presents the design of two ground based synthetic aperture radar (GB-SAR) systems working at 94 and 300 GHz respectively. Frequency-modulated continuous-wave (FM-CW) technique is used for both systems, being described in the first section. Afterwards the first design at 94GHz is presented, explaining its geometry of exploration and describing the architecture of the W-band radar setup. Regarding the integrated receiver system, two models of low noise (LNA) and medium power amplifiers are disclosed, presenting noise figure and S parameters curves comprising frequencies between 75 and 110 GHz (W-band). Finally the second radar setup working at 300GHz is presented, depicting the hardware block diagram and explaining the main performance parameters of the system.**

I. INTRODUCTION

FM-CW radars offer the advantage of achieving moderate illumination energy of the scene area with low transmitted power. Moreover if a linear FM is used both in transmission and echo down-conversion, the compression of the echo spectrum allows using low cost slow A/D converters to digitize the signals reflected by small areas of interest. Direct Digital Synthesis technology is usually adopted for low phase-noise linearly modulated signal. In this way several versions of FM-CW radar have been developed for Remote Sensing applications at C, X and Ku Bands [1][2]. Low power systems can be used in a Ground Based configuration for a number of short range applications like high resolution SAR imaging, SAR interferometry and SAR polarimetry [aguasca 2009, GRS Letters].

In this context the paper presents the design of two FM-CW Ground based SAR (GB-SAR) systems working at 94 and 300 GHz respectively. Increasing the carrier frequency close to the THz range allows using very compact synthetic apertures with decimetric cross range resolution. Similarly the FM bandwidth can be increased in the order of several GHz results in a fine range resolution in the order of 10 cm Proposed applications for such systems are imaging for security reinforcement and stability control of buildings and infrastructures. The technological aspects are critical in these very high frequencies due to the integration difficulties of the basic devices such as LNA, Mixers, etc. in a compact and low-loss layout.

II. FM-CW SAR BACKGROUND

Synthetic Aperture Radar is an imaging modality that addresses the general problem of forming a target region reflectivity function in the multidimensional spatial domain of range (x), cross-range (y) and altitude (z). For a single image acquisition, the range and altitude variables combine in the slant-range domain, $z = \sqrt{x^2 + y^2}$. The height of the targets can be determined with an interferometric approach, with at least two images taken from different positions [3][4]. The transmitting/receiving radar is mounted in a moving platform, that can be placed either in satellites (orbital SAR), airplanes (airborne SAR), or rails (GB-SAR).

In FM-CW radars, a chirp signal is transmitted for certain duration. While it is transmitting, the echoes are received by the receiver and mixed with the transmit signal, and the result is low-pass filtered to produce a superposition of beat frequencies. In this way the receiver for an FMCW system measures the difference in frequency between the transmitted and received signals. The difference in frequency between the transmitted signal and the signal received from a scattering target is referred to as the beat frequency, Fig.1b. The beat frequency is directly related to the range and velocity of the target. To achieve so, range resolution requires wide bands in the frequency domain, that is, sharp pulses or chirps in time. On the other side achieving good Doppler resolution requires a sharp pulse spectrum, this is a long duration pulse in time. There is not a feasible system working with a single pulse, then, a signal which is composed of several repeated sharp bursts over long intervals in both time and frequency domains is transmitted. This form of transmission is known as time-frequency diversity signaling; two common forms of FM-CW modulation are triangular, Fig.1a, and sawtooth. The repetition of a pulse over long time duration is an approximation to a periodic signal with discrete spectral distribution, providing good Doppler resolution. It must be pointed out that two assumptions are usually made. On one hand the round-trip delay is much smaller than the pulse repetition interval (PRI). On the other hand the transmitted signals' baseband bandwidth is smaller than the carrier frequency.

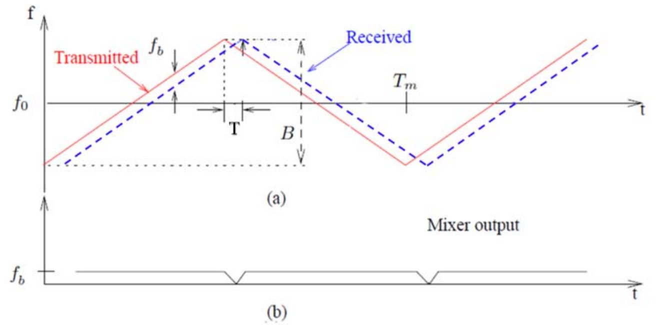

Fig1. a) Transmitted and received signal from a target object. In which T, B, T_M are the round trip time, the bandwidth of the transmitted signal, the, and the period respectively. b) Beat frequency, f_b, between transmitted and received signals

III. FMCW RADAR SYSTEM AT 94 GHZ

A. Geometry of the GB-SAR observation

The main performance parameters for GB-SAR operation can be obtained taking into account the geometry of observation. Fig. 2 depicts a typical GB-SAR scene observation, the radar with its transmitter-receiver antennas is displaced with a linear positioner in order to form the synthetic aperture. This radar setup is placed on the top of a building pointing towards a desired object over the ground plane with a specific angle. The grey area inside the circle represents the footprint of the antenna at a certain moment, whereas the two dark bands along the x and y show the azimuth and ground range resolution respectively. Regarding the antenna, L_a is the antenna size, L_s is the synthetic aperture length, and v_p is the velocity which the antenna is moved over the rail mounted along the x axis.

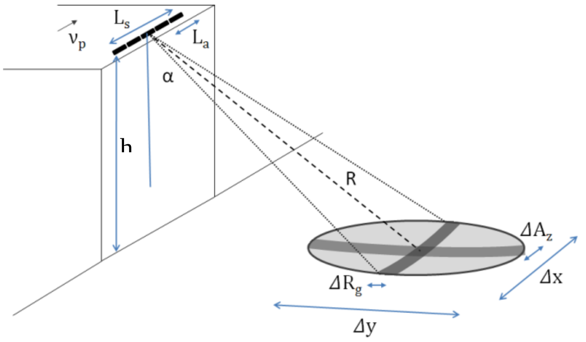

Fig 2. System geometry of exploration for synthetic aperture radar

Assuming a height of 10 meters, a synthetic aperture of 30cm, antenna size of 1.5cm, incidence angle of 60 degrees, and a displacement velocity of 5 mm/s, an azimuth resolution of 10 cm at a 20 meter range is achieved. Considering a bandwidth of 1GHz a ground range resolution of 15cm at 20 meters distance is attained. In order to fulfill the specifications, the valid range of pulse repetition frequencies (PRF) is comprised between 0.6 Hz and 13.5 GHz.

B. Setup description

The block diagram of the W-band radar system architecture is shown in Fig.3. The system has been conceived to be work at 94 GHz, including the capability of an easy change of the frequency operation, thanks to the programmable PLL and DDS which are controlled by a computer. The four main modules of the SAR are described below.

- *Frequency generation stage*

The first block is the frequency generation stage, which includes a programmable FM-modulated frequency generator based on a Direct Digital Synthesis. For the design a commercial device has been considered, AD9858 from Analog Devices, and controlled by a PIC microcontroller. This module can generate the desired triangular FM modulation, which is synthesized via a step frequency change preserving phase continuity, leading hence to a better quality signal.

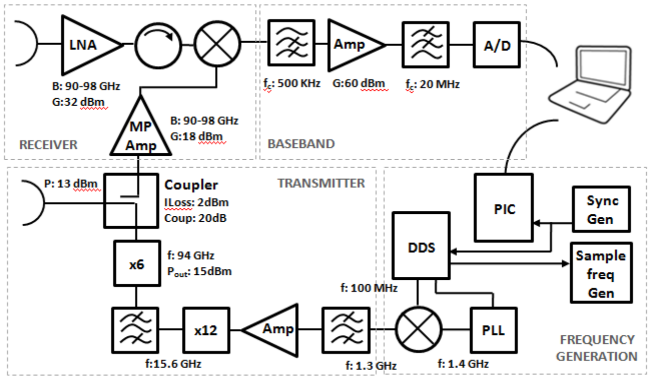

Fig 3. Block diagram scheme of the system

In the generation module the basic logic circuitry for the Pulse Repetition Frequency (PRF) is also included. These signals are extracted from the same reference clock used by the DDS, reaching a perfect synchronization between the frequency ramp origin and the start of A/D sampling. A band pass filter has been included at the output of the generation module to eliminate the undesired replicas.

- *Transmitter*

The transmitter module uses two frequency multiplier stages in order to upconvert the operational frequency up to 94 GHz. By performing the frequency band translation the bandwidth is increased as well. In this case the original 20 MHz bandwidth is transformed through the frequency multipliers by a factor of 72 to a 1.44GHz bandwidth chirp. A bandwidth band pass filter is included to reduce spurious and non-desired harmonics generated by the active multiplier. Finally two identical conical horns are used for transmission and reception providing the required isolation to avoid reception saturation.

- *Receiver*

The receiver front-end a low noise amplifier (LNA), and a homodyne stage which performs the down-conversion by means of a mixer. Also an isolator is included in order to attenuate the undesired returning signal coming from OL. A medium power amplifier is used for the OL signal to compensate the coupler factor. Assuming a maximum range of 500 meters, a chirp bandwidth of 1.44 GHz, it leads to maximum f_b (beat frequency) of 160MHz. If the range is reduced to 20 meters, it results to a 6.4MHz f_b.

- *Base Band Stage*

Since the frequency axis of the base band is proportional to target range, a highpass filter is included before the video amplifier in order to ensure the proper dynamic range compression for signal compensation. Then a low pass filter is used such that the cut frequency is suited according to the maximum beat frequency given by the maximum range. Finally a high speed A/D stage digitalizes the signal in order to be processed by a computer.

IV. INTEGRATED RECEIVER SYSTEM

To integrate critical high frequency parts of the receiver (LNA, mixer, MPA to drive LO signal, etc.) in a compact structure the tooling of a metal case is considered.

Such a case would have two WR10 waveguide inputs and an output with 3.5 mm or SMA. Depending on the possibility of integrating the isolator, two additional waveguide accesses would be required. The final performance of the mixer in terms of LO-RF isolation will be a key factor. Mixing with fundamental LO, not with a sub harmonic makes this parameter more critical and makes the isolator unavoidable. Another possibility is the use of half LO and sub harmonic mixing.

There are two alternatives for the LNA functionality:

- An own-developed design with D007IH technology (OMMIC) [5] that consist of a cascode gain stage providing gain between 94 and 100 GHz with a maximum of 12 dB at 97 GHz. To reach the required gain level, 3 cascaded units would be required. Noise figure is plotted in Fig. 4.

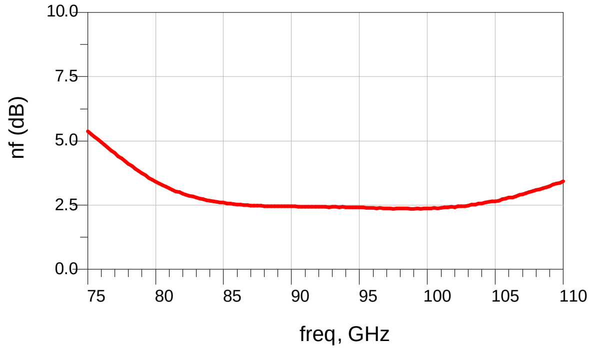

Fig. 4 Noise figure of the 3 cascode LNAs chain

- A commercial MMIC (LNA5 HRL) which provides the required gain in a broader band, but with a Noise Figure around 3 dB. Gain and reverse isolation are plot in Fig. 5.

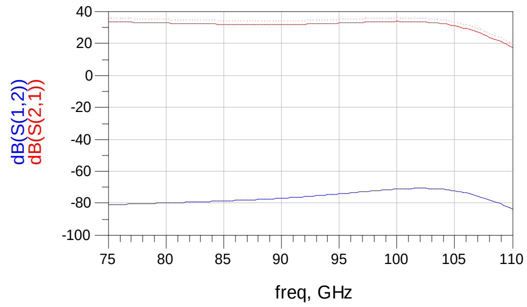

Fig. 5 S_{21} and S_{12} (dB) of LNA5 (HRL).

Two possibilities are considered for the medium power amplifier:

- An own-developed MMIC design, also with OMMIC technology (D01MH) [6] which, according to the simulations, provides small signal gain of about 14 dB and 1dB-compressed output power of 19 dBm at 97 GHz. In Fig. 6 large signal gain is depicted sweeping the input power from -20 to +15 dBm.

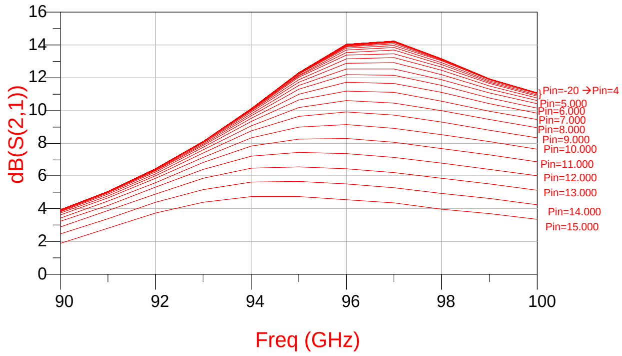

Fig. 6 Large signal S_{21} (dB) P_{in} swept from -20 dBm to 15 dBm.

- A commercial MMIC, also produced by HRL (LSPA2) with a typical small signal gain of about 13dBm and 1dB-compressed output power of 13 dBm. Small signal gain and input/output matching of a sample unit are shown in Fig. 7.

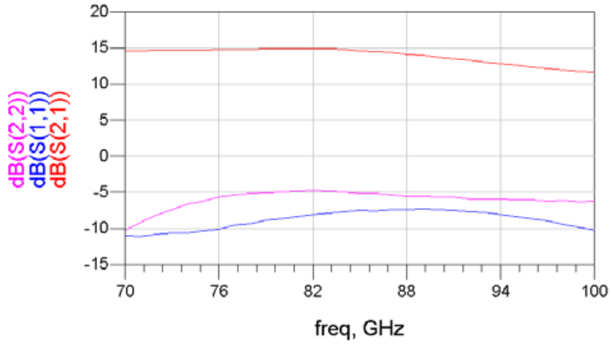

Fig. 7 S_{21} , S_{11} and S_{22} (dB) LSPA2 (HRL).

Two types of diodes are available for the development of the mixing function: “single anode” and “anti-parallel”, manufactured by Virginia Diodes. The first type could be suitable for LO fundamental mixing, and for sub-harmonic mixing (OL/2) the second can provide inherent LO cancellation. The most optimistic expected conversion losses are around 5 ó 6 dB. A photo of an anti-parallel pair assembled for coplanar probes characterization with J-micro system [7] is shown in Fig. 8.

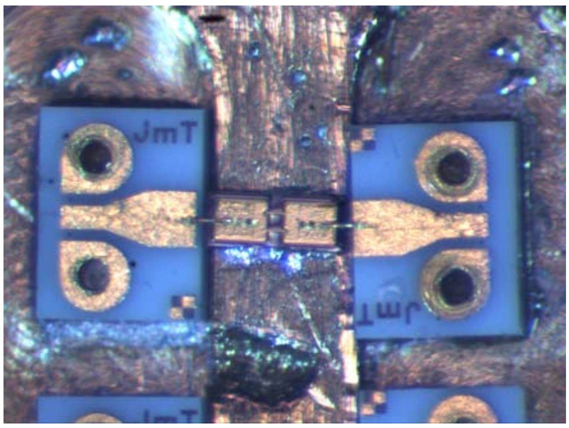

Fig. 8 Anti-parallel diodes assembled for characterization with coplanar probes.

V. FMCW Radar System at 300 GHz

A block diagram of an FMCW radar system is shown in Fig. 9. It is a high-resolution radar that consists of a front-end of commercial components operating at frequencies up to 300 GHz. The bandwidth of the system goes from 280.8 to 307.8 GHz and has been selected to be inside a window of atmospheric attenuation. In that range of frequencies, the value of attenuation is ~5 dB/km [3]. Taking into account that the ranges for the intended applications are only a few metres, the losses due to atmospheric absorption are practically negligible.

The radar is a frequency multiplier-based homodyne system. It transforms a chirp signal of a certain bandwidth, which is generated at microwave frequencies, into another one centered around 300 GHz with its bandwidth scaled up by the multiplication factor of the chain.

As shown in Fig. 9, a direct digital synthesizer (DDS) is used to generate a chirp signal, ramping from 0.2 to 0.7 GHz in a maximum repetition interval of 1.5 ms. By using this module, a good linearity of the ramp waveform is ensured, as well as versatility for signal parameters configuration. Then, the chirp is upconverted after being mixed with a 5 GHz carrier, generated from the 2.5 GHz output signal of a frequency synthesizer. It is also the clock signal for the DDS.

Fig. 9 shows an area limited by dash-dot lines. It represents the microwave module, which integrates all of the components operating below 17 GHz. From that point on, the components of the transmitter are designed and implemented in waveguide technology.

After being multiplied and amplified, the signal ramps over a bandwidth of 27 GHz (280.8 - 307.8 GHz), with a power level between 0 dBm and -3dBm. This bandwidth results in a range resolution of 5.5mm, calculated by the well-known expression $\Delta R=c/2B$, where c is the speed of light and B is the signal bandwidth.

The signal is transmitted linearly polarized by using a conical horn antenna with a BW_{-3dB} of 30º. Corrugated horns with lower HPBW, e.g. 10º, are also a valid alternative for the application. When the wave reaches the targets, part of the transmitted power is reflected depending on the reflectivity of the material that scatterers are made from [8].

The reflected signals reach the horn antenna in the receiver. Apart from the horn antenna, the receiver chain basically consists of a subharmonic mixer, which requires an LO signal at half of the RF signal frequency, i.e., around 150 GHz.

It is generated by multiplying a sample of the chirp signal collected at a certain point of the transmission chain. The resulting IF signal contains the information about the beat frequencies corresponding to the different targets. The range profile is obtained from that spectral content in the subsequent digital signal processing subsystem.

Table 1 summarizes the main performance characteristics of the system described in this section.

FMCW radar @ 280.8-307.8 GHz	
Bandwidth (B)	27 GHz
Maximum chirp period (T)	1.5 ms
Range resolution (ΔR)	5.5 mm
Transmitted power (P_t)	0/-3 dBm
Noise figure (NF)	7 dB

Table 1: Operation parameters of the radar at 300 GHz

It is worth mentioning that, as an intermediate development stage, measurements at frequencies around 100 GHz can be carried out by reassembling the transmission chain up to 100 GHz and exchanging the horn antennas and the mixer for others with suitable characteristics for operation at 100 GHz.

Acknowledgments

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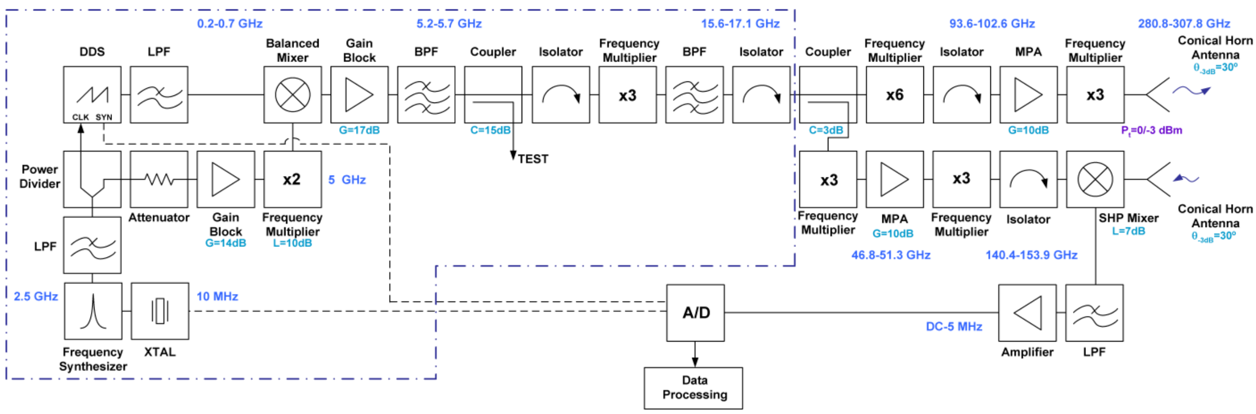

Fig. 9 Block diagram of a 300GHz FMCW radar system