SUB-MILLIMETER WAVE RECEIVERS

Pedro de Paco[(1)], Antonio Tazón[(2)], Oscar Menéndez[(1)], Juan Pablo Pascual[(2)], Josep Parrón[(1)], Tomás Fernández[(2)], Gary Junkin[(1)], Jessica Gutiérrez[(2)], Kaoutar Zeljami[(2)]
{Pedro.depaco, Josep.parron,Oscar.menendez, Gary.junkin}@uab.es,
{Antonio.tazon, Tomas.fernandez, Pascualp, Zeljamik,Jessica.gutierrez}@unican.es
[(1)] Dpto. de Telecomunicació i d'Enginyeria de Sistemes. Universitat Autònoma de Barcelona.
[(2)] Dpto. de Ingeniería de Comunicaciones. Universidad de Cantabria.

***Abstract*- In this article a review is carried out of how technological aspects are affecting the system configuration of a sub-millimeterwave receiver for imaging applications. Throughout the discussion we will emphasize the role that the Schottky diode plays in this type of applications.**

I. INTRODUCTION

Imaging applications in areas such as biology, medicine, security or defense are emerging, enabled by the technological advances carried out in the sub-millimeter wave range. Several opportunities are only awaiting a much less costly instrumentation before their widespread use.

For small targets at close range, time-domain spectroscopy techniques seem to be best suited. For this reason, we are going to focus here on systems operating with longer standoff distances and wider fields-of-view.

The particular penetration and loss characteristics of millimeter and sub-millimeter wave signals provide a contrast diversity that may be advantageous for imaging system. Sub-millimeter wave radiation can penetrate many common plastics and crystals as well as common fabrics, dry chemicals and foodstuffs. Although propagation is not attenuated in excess by smoke, dust, fog or drizzle rain inside the 100 GHz window this systems may vary greatly depending upon the weather conditions. On the other hand, poor conductors and especially aqueous materials are extremely absorptive and prevent penetration (and imaging) much below the outer layers.

For biology or medical applications sub-millimeter wave imaging has been applied in the diagnosis and detection of skin-cancer. Despite the broad spectral absorption signatures in liquids and solids, sub-millimeter waves haves also been proven for substance identification of both chemical and biological systems succesfully. Many industrial applications involving the quantification and monitoring of moisture content has been proposed, for example the European project KOKON tested the absorption of automotive paint. Recent attention has focused on security applications since sub-millimeter wave signals can penetrate many garments providing low resolution images of the body and on defense applications for all weather tactical data links.

II. SYSTEM ARCHITECTURE

Aimed at highlighting several technological key points, a brief architectural review will be carried out from a systemic point of view. The discussion is focused on comparing different solutions with respect to the illumination nature of the scene, the receiver architecture and the scan strategy.

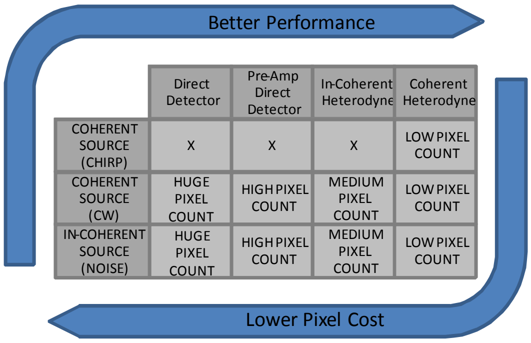

Fig. 1. Trade-off between illumination nature and receiver coherence.

In order be objective while evaluating factors influencing the signal to noise ratio, we will make use of two key parameters: the number of pixel composing an image frame and the dwell time of a beam detector on a pixel.

We start with a system based on a non-coherent illumination, where a passive sensor or radiometer takes advantage of the spectral distribution of natural radiation by means of emissivity and reflectivity diversity for imaging.

A diode direct detection receiver evidently is the most cost effective solution and in active research continues as being the most suitable option for a focal plane array (FPA). However, such a receiver limits the total thermal energy from the scene that falls on the rectifying element because of single-mode operation, intrinsic frequency responsivity and mode-matching antenna coupling.

Focal plane direct detection arrays are easier to realize in this frequency range since there is no LO and the interface is limited to only the DC output detected voltage.

The signal-to-noise ratio of direct detection receivers for the temperature contrast between a warm body and the background is given by the Dicke relation expressed in terms of the detector noise equivalent power (NEP).

$$\left.\frac{S}{N}\right|_{DD} = \frac{\left(T_{SKY} - T_{BODY}\right)}{NEP} KB_{e-RF}\sqrt{\tau_{\text{int}}} \qquad (1)$$

It is evident that a FPA detector will have all the observation time available for signal integration. Hence, for outdoor operation, where the temperature contrast can exceed 100 K, it seems feasible to obtain SNR greater than unity using commercial devices, even with a sub-second imaging system. However if the contrast temperature falls to 10 K, as occurs in indoor operation, especially for values of reflectivity and transmissivity that are below unity, passive imaging is simply not realistic with available technology. Despite this, direct detection continues generating considerable interest and the state of the art will be revised in section III.

It is widely accepted that if a instrument is limited by the detector noise, the direct detectors will be potentially more sensitive than heterodyne instruments where the quantum noise limit is present.

However, for a background noise limited instrument, both heterodyne and direct detectors have similar sensitivities. The main advantage of a heterodyne receiver is in the acquisition of weak and narrow-band signals, where the amplification stage of direct detection adds so much noise, that makes necessary long integration times to recover the signal, requiring extra efforts to implement continuous calibration schemes to compensate drifts and flicker noise.

Heterodyne receivers come into play in an environment where sensitivity is limited by the noise power from the scene since the system noise is limited through a post-conversion filter. In such cases, there is no need to utilize detectors with NEP below background noise.

The signal to noise ratio for either a heterodyne receiver or a pre-amplified detector is given by the Dicke relation expressed in terms of the equivalent input noise temperature and considering only a white noise source.

$$\left.\frac{S}{N}\right|_{HET} = \frac{\left(T_{SKY} - T_{BODY}\right)}{T_N}\sqrt{B_{e-RF}\tau_{\text{int}}} \qquad (2)$$

There are many difficulties related with defining and operating a heterodyne instrument in the sub-millimeter wave regime. Amongst these, the following two difficulties are the most important, especially above 100 GHz: (1) a lack of commercial component technology for the RF source and down-converter modules and (2) the complexity in routing the meagre power level provided by a local oscillator source.

It is a fact that the major efforts carried out for developing heterodyne receivers at submillimeter wavelengths are based on single pixel architecture. Nevertheless, in a multi-pixel heterodyne array instrument, the available OL power is, without doubt, a major concern. For these reasons, the available OL power will ultimately decide the mixer configuration and the tradeoff between pixel count and dwell time for such an array.

Assuming the availability of a suitable active source, two different approaches can be stated according to the receiver architecture. The first one is a non-coherent or scalar receiver architecture, for both direct detection or heterodyne receiver. The simplest approach takes advantage of raising the equivalent contrast temperature. However a better approach can be suggested with indirect holographic techniques enabling to use only amplitude detection. The procedure is based on back-propagation of a complex electric field retrieved by applying a reference wave, which creates an interference pattern with the wave reflected from or transmitted through the target.

The second is preserving the phase information that allows for image reconstruction techniques necessary for synthetic aperture radars. However, active illumination has the disadvantage of glint effects (speckle) in the image.

Taking advantage of spatial coherence function measuring the electric field from a source at two locations at the same time it is possible to reduce the number of receiver filling a reduced sparse array. The van Cittert–Zernike theorem states that for sources in the far field the normalized value of the spatial coherence function is equal to the Fourier transform of the normalized scene brightness distribution. Therefore, the correlation of the electric fields at two different points, allows the recovery of the source via an inverse Fourier transform of the visibility function. The sampling must be made for a suitable set of vector baselines. Several examples can be found like the Mill-cross or even for passive systems the Y-shaped array of SMOS instrument. For a given number of detectors N, there are N(N-1)/2 possible baseline combinations. Even so, the number of receivers remains prohibitive and it continues being a challenge.

To end the discussion, it is interesting to point out some considerations about the scan strategy. In a staring array of low cost passive sensors each detector uses all the observation time for signal integration, hence the advantages are evident in regards of sensitivity.

However, for active systems a scanned strategy will be more sensitive since the illumination can be focus on just those pixels being observed each instant of the scan. Otherwise, a staring array does not result in a great advantage since the noise scales as root square of the number of pixels through the integration time sharing and the illumination power will scale as the number of pixel through the quotient between field of view and sensor equivalent solid angle.

Hence, a scanning system would be preferred for an active scheme, however, even the fastest proposed methods based on rotating or tilting lightweight secondary mirrors for rapid beam deflection are limited by the rotational rates required in a 2-D sub-second imagers [1][2].

An alternative to the fast scanning problem would be to take advantage of building a linear array of many parallel receivers with beams scanning into a single direction to obtain a full scene.

With this panorama, while lithographic micromachining can help to distribute the RF, OL and IF signal in a compact receiver array, generation of coherent terahertz radiation remains a critical technological challenge. The lack of compact, reliable, efficient and broadband sources in the terahertz range is without doubt a key. Sources are required for all possible applications, either as transmitters or as local oscillators (LO) for heterodyne detectors.

According the previous discussion the Schottky diode is presently a keystone for large signal devices such as mixers and frequency multipliers, but also for small-signal application such as square-law detection. In the next sections will be reviewed the role played by the Schottky diode.

III. Direct Detector based on Schottky diode

As previously stated, passive systems must solve a fundamental trade-off between sensitivity and imaging speed. The tradeoff is given by the upper bound in the temperature difference between a body and the thermal environment. According to (1), and taking a small signal Schottky diode with a beyond state-of-the-art noise equivalent power of 1 pW/√Hz and a fractional bandwidth around 30 % is insufficient to obtain signal to noise ratio higher than 1 for temperature contrast ranging between 1K to 10 K.

The noise after detection can be approximated by two voltage-noise spectral density terms (disregarding shot and burst noise): Thermal noise and flicker noise. Therefore, the specific NEP after detection is given by:

$$NEP = \beta^{-1} \cdot \sqrt{4K_B T_j R_j + K_f \, {V^2}/{f}} \qquad (3)$$

where β is the responsivity, R_j the junction resistance, q the electron charge, V the forward voltage ($S_V=S_I R_j^2$), K_B boltzman constant, T_j the junction temperature and K_f a flicker noise constant.

For very small signal input, the Noise Equivalent Power will reach a minimum very close to the responsivity maximum, and the flicker noise will limit the NEP.

When the diode is optimized to have a low forward turn-on voltage, the detectors can achieve excellent frequency response and bandwidth, even with zero-bias. Under low power operation, Virginia Diodes has reported measured detectors based on schottky barrier achieving a NEP of about 1.5 pW/√Hz without signal modulation and with a resposivity about 3000 mV/mW at 150 GHz over more than 40% relative bandwidth, rising to approximately 20 pW/√Hz at 900 GHz.

But it must be pointed that such high sensitivity will happen for any zero-bias diode detector only with high responsivity and while there is no incident RF power; since only thermal noise can be generated under this condition.

In other words, as the input power is increased, excess noise is generated with a typical $1/f$ power spectrum. The flicker noise increases roughly linearly with the applied power due to a linear increase in the rectified current through the junction. Then signal modulation will begins to be generally required to achieve maximum sensitivity.

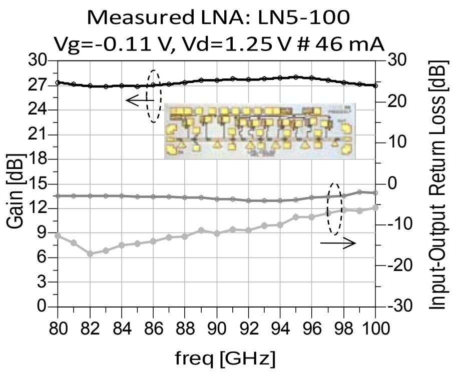

Fig. 2. Gain and input-output return loss mesured at bias conditions (Vg=-0.11V, Vd=1.25 V, Id=46 mA).

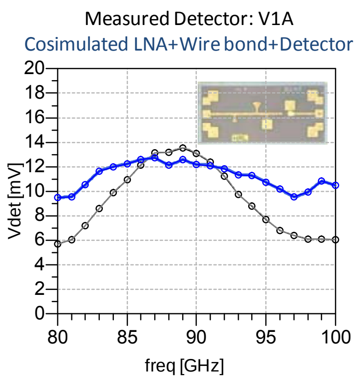

Fig. 3. Detected voltage vs frequency. The input power is -60 dBm for the preamplified detector (blue line).

On the other hand, HRL has proposed the use of backward diodes for millimeter-wave square-law power detection. The proposed Antimonide based heterostructure provides a device with low capacitance (10 fF), low resistance (2KΩ) and a highly nonlinear current versus voltage characteristic, resulting on an intrinsic rectification efficiency (before matching) about 30 mV/μW, at zero bias.

In addition, backward diodes are relatively insensitive to temperature, as the tunneling current is not thermally activated in the desired nonlinear bias regime.

The combination of low resistance (and thus Johnson noise) and high sensitivity results in a noise equivalent power of 2.4 pW/√Hz at 94 GHz for a conjugately matched source, whereas the reduced capacitance facilitates wideband matching and increases the detector cutoff frequency.

This solution has enabled the use of a preamplified detector based on a InP HEMT LNA requiring only 25 dB of gain (see Fig. 2), that reduces overall cost. Furthermore, the low noise level of the sensor allows us to achieve a NETD<0.5 K including the flicker noise without a continuous calibration scheme [3]. This low-signal NEP could be improved by optimizing the signal coupling to the detector over a narrower frequency band. Nevertheless, it is also true that the detector is perhaps more useful for broadband applications.

IV. The Schootky Diode As a Key Element on Heterodyne Scheme.

The output power of a source is itsmost important figure of merit, however, from a systems point of view it is also important others aspects such as tuning bandwidth, frequency stability, DC-to-RF conversion efficiency or spectral purity that can dispose the usability of any particular technology.

Recently hetero-junction barrier varactor diode (HBV) has been proven with promising results. The goodness of HBV diode for odd multiplier schemes is obtainded thanks to the even symmetry of the C-V characteristic and the anti-symmetry of the I-V characteristic, so that only odd harmonics are generated. Moreover, efficiencies up to 20% have been measured at 100 GHz due to a higher power handling capacity while keeping the device electrically small.

In any case, the junction Schottky diode in either as a discrete planar or as a planar monolithic device forms is the most dominant technology for generation of microwave power. Measured efficiency is around 25 % for doubler configuration while it falls to 5-10% for tripler configuration, that means a reported output power at room temperature around 10 mW at 300 GHz [4]. Multiplier based oscillator chain based on Schottky diode has been enabled by the development of high power GaAs MMICs in the 100 GHz range with output power up to 150-200 mW. They are continuously tunable over 10-15 % of bandwidth.

These approaches have its limitations and would have to be extremely well optimized to pump multi-pixel receivers or provide useful power at sub-millimeter wave region. However, to make this is necessary to improve the device models because the simulated output power and efficiency are usually higher than those obtained by measurement.

A simple diode model with nonlinear resistor and nonlinear capacitance can be successfully used to look at the limitations of the device. Consider the diode as a uniformly doped semiconductor structure with their ohmic contact and metal-semiconductor contact. The depletion layer can be modeled as a capacitor and the undepleted region of the structure can be modeled as a resistor. The depletion layer will act as a parallel plate capacitor where the capacitance variation is achieved by modulating the depletion width.

This inverse square root dependent capacitance is the starting point for analytic varactor analysis. Similarly, under forward bias, the device current will be an exponential function of the applied voltage, giving rise to the non-linear resistance. Submillimeter-wave frequency multipliers often work in a mode that is really a combination of both.

The undepleted region of the device and package resistances will appear in series with the nonlinear junction.

Although the undepleted region width is voltage dependent, this series resistance is usually modeled with a constant value and usually obtained measuring the asymptotic behavior of the I/V curve for a forward biased barrier. However, at very high frequencies the current through the undepleted region can flow by the outside edge of the material due to the skin effect, increasing the resistance. So, it is necessary to include this frequency dependent resistance in any model to obtain fitted performance predictions.

Other important question is the limited carrier velocity in GaAs that determines an upper bound for the rate of change of the space-charge width. This rate depends on a combination of the frequency, RF and DC voltages across the device and the doping [5]. If the rate is larger than the saturated velocity imposed by the semiconductor, the voltage dependent description of the calculated capacitance will not be correct. Driving the device beyond this saturation point will increase the voltage drop and resistance of the undepleted region and reduce the conversion efficiency of the frequency.

Another important consideration is the bias conditions for the frequency multiplier circuit. Current saturation theory suggests using a high doped semiconductor; however, this decreases the breakdown voltage of the device and can result in limiting output power from the device.

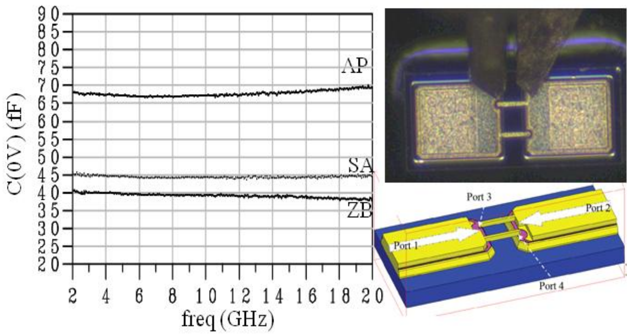

Fig. 4. Measured total capacitance Antiparallel, Single Anode and ZB diode and 3D representation of a antiparalell diode pair [6].

Discrete planar diodes are limited in frequency due to their size and the difficulty to connect them to the carrier circuit with sufficient precision. Circuit loss and parasitic effects also increases with frequency, so the loss between the diode and the external connection should be carefully modeled. Electromagnetic 3D simulators are being used to evaluate dielectric loading effects over the junction and substrate lift-off techniques it has been succesfully used to reduce these effects [6]. Fig 4 shows the measured total capacitance of a single anode, antiparallel and zero bias W-ban diode. Although the results reveal a systematic 15 fF parasitic capacitance due to a 100 µm pith differential probe, the measurement is made without a test fixture. The measured electrical characteristics are very close to device specification.

To end, any successful design must be accurate with the input and output device coupling. It is very difficult to provide a purely reactive match to the device for maximum coupling efficiency.

The availability of LO power also dictates the mixer technology. There are at least three different technologies that could be considered for an array receiver design. Superconductor insulator superconductor (SIS) mixers are the most sensitive mixers available today in the sub-millimeter wave range. The reported double sideband (DSB) noise temperatures are about 100 K at 500 GHz while requiring approximately 40–100 µW of LO pump power. Hot electron bolometer (HEB) mixers have also good noise performance. Typical DSB noise temperatures of HEB mixers are around 600 K at 500 GHz. They require approximately 2 µW of LO pump power. However, both SIS and HEB mixers typically operate at temperatures below 4 K.

One of the major advantages of Schottky mixers compared to SIS and HEB mixers is that they operate at room temperature. However, Schottky mixers require high local oscillator pump power, approximately in the 1-3 mW range. The status of subharmonic mixers shows that typical DSB noise temperatures for room temperature Schottky mixers are about 500 K at 100 GHz and about 1800 K at 500 GHz with approximately 5 dB and 8 dB of conversion loss respectively.

V. Conclusion

Imaging applications in areas such as biology, medicine, security or defense are emerging enabled by the technological advances carried out in the sub-millimeter wave range. Several opportunities are only awaiting for a much less costly instrumentation before their widespread use. The necessity of low cost and high performance components to be part of a large array is a common challenge in any system solution.

Acknowledgment

This work is supported by the Spanish Comisión Interministerial de Ciencia y Tecnología (CICYT) del Ministerio de Ciencia e Innovación and FEDER funds through grant TEC2009-13897-C03-02 and CONSOLIDER INGENIO 2010 program, reference CSD2008-00068.

Referencias

[1] E. N. Grossman, A. Luukanen, and A. J. Miller, "Terahertz active direct detection imagers," Proc. SPIE 5411, 68–77 (2004).

[2] K. B. Cooper, R. J. Dengler, N. Llombart, T. Bryllert, G. Chattopadhyay, E. Schlecht, J. Gill, C. Lee, A. Skalare, I. Mehdi, and P. H. Siegel, "Penetrating 3D Imaging at 4 and 25 Meter Range Using a Submillimeter-Wave Radar," IEEE Transactions on Microwave Theory and Techniques 56, 2771–2778 (2008).

[3] JJ Lynch, HP Moyer, JH Schaffner, Y Royter, M. SokolichB. Hughes, Y. J. Yoon, J. N. Schulman, "Passive Millimeter-Wave Imaging Module With Preamplified Zero-Bias", IEEE Transactions on Microwave Theory and Techniques, vol. 56, no. 7, july 2008

[4] Mehdi, J. Ward, A. Maestrini, G. Chattopadhyay, E. Schlecht, J.Gill, "Pushing the Limits of Multiplier-Based Local Oscillator Chains", 19th International Symposium on Space Terahertz Technology, Groningen, 196-201, April 2008

[5] Grajal, J.; Krozer, V.; Gonzalez, E.; Maldonado, F.; Gismero, J.; "Modeling and design aspects of millimeter-wave and submillimeter-wave Schottky diode varactor frequency multipliers", Microwave Theory and Techniques, IEEE Transactions on, V: 48 ,700-711 (2000)

[6] Thomas B. "Etude et réalisation d'une tête de reception hétérodyne en ondes submillimétriques pour l'étude des atmosphères et surfaces de planètes", PhD dissertation, 2004.