Design of a Combined Tripler-Subharmonic Mixer at 330 GHz for Multipixel Application Using European Schottky Diodes

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***Abstract*—We present the development of an integrated heterodyne receiver at 330 GHz featuring a balanced tripler and a sub-harmonic mixer embedded on the same substrate. The receiver block has one face dedicated to the feed aperture, and the opposite face to the local oscillator input and the intermediate frequency output. By utilizing only opposite faces this configuration makes building of a full two-dimensional array possible through stacking receiver elements. Moreover, the size of the receiver block is minimised by a small spacing between the mixer and its local oscillator circuit. The input signal of the multipler stage is between 55 and 60 GHz where high power sources are more commonly available than at sub-millimeter frequencies. A preliminary design and its analysis are described in order to enlight problematics related to circuits composed of several non-linear elements. Packaging constraints are also discussed here since the spacing between two horn antennas is limited by the physical size of the local oscillator and IF connectors on the back face of the pixel.**

***Index Terms*—Frequency Tripler, Sub-harmonic mixer, Heterodyne arrays, Spurious signal, Submillimeter-wave.**

I. Introduction

Theoretical studies of atmospheric sounding from space borne instruments have shown that sub-millimeter wave radiometry offers new perspectives for the characterization of clouds and rain on a global scale. Moreover, the non-ionizing properties of sub-millimeter and terahertz radiation and the relatively low power levels generally required make its use safe for bio-medical diagnostics. Sub-millimeter radiation also has the remarkable property of having only moderate attenuation while propagating through non-polar materials such as paper, wood, glass, plastic or ceramic, and is demonstrably useful for security screening, explosives and contraband detection. The list of applications at millimeter and sub-millimeter wavelengths continues to grow as new fields emerge through the development of increasingly mature technology. Several of these developments are focused on technologies for heterodyne focal plane arrays, in order to ally higher sensitivity, greater mapping speed and large-scale mapping ability [1]. In this context, more widespread use of array receivers will be encouraged by the availability of integrated components with appropriated packaging. In particular, Schottky array elements give the advantage that they will work at ambient temperatures. The current work is part of a program dedicated to Schottky diode receiver array development, conducted at the Rutherford Appleton Laboratory and held in collaboration with the Observatory of Paris. The motivation for building these receivers is the applications in atmospheric sensing particularly observations of cirrus cloud at Sub-millimeter frequencies (EUMETSAT post-EPS and EU/ESA GMES Sentinel programmes).

A. Circuit Configuration

The main issue for the development of heterodyne receiver array is the integration of components at a high level with special care given to power transmission and dissipation. Mass production, repeatability, miniaturization, and the use of MMICs are also key issues for arrays fabrication. To resolve these questions, it is necessary to optimize the interface between the mixers and the local oscillator unit.
Two different configurations can be used to integrate the mixer and the frequency multiplier; either integrate the mixer and multiplier that are based on separate substrate via waveguide component [2] or combine the mixer and the frequency multiplier on a single substrate [3]. The optimum performance

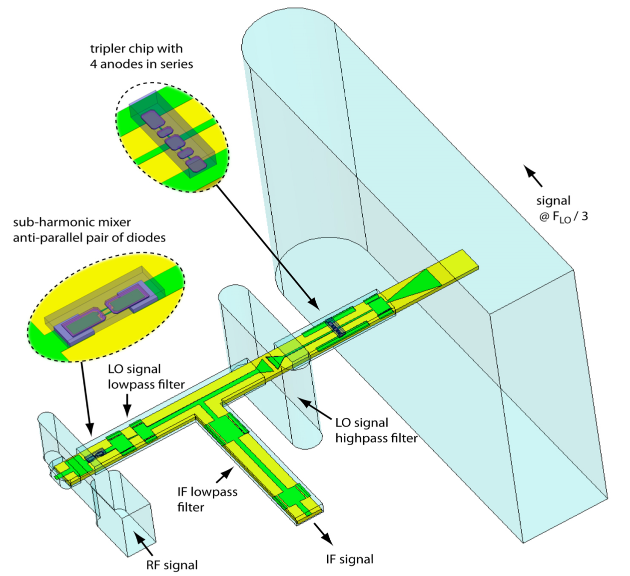

Fig. 1. HFSS view of the preliminary combined tripler/subharmonic mixer design. The high pass filter is not included in the presented results.

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of the mixer and the frequency multiplier generally require respectively different epitaxial doping layer of the substrate not possible in the combined circuit case. Nevertheless, the integration of a mixer and multiplier on a single substrate offers a simpler assembly work and higher integration level, which are suitable for large array development.

The block presented in this paper features a combined circuit composed of a balanced tripler and a sub-harmonic mixer integrated within the same circuit. The input signal of the multiplier stage is between 55 and 60 GHz where high power sources are more commonly available than at sub-millimeter frequencies. At E band, commercially available power sources[1] are reaching 27 dBm so make it possible to pump four integrated receivers with the same source.

Both multiplier and mixer are unbiased, which means in the tripler case working in the varistor mode, therefore with limited efficiency. It allows to reduce the number of connectors and also favorises easier operation than with biased circuits. The mixer and multiplier circuits are balanced. For the tripler, this leads to an impedance close to pure reactance at the second (idler) harmonic of the input signal [4]. If we consider 20 dBm power at the multiplier input for each of the receiver, the tripler predicts to reach efficiency of 2 to 4 percents enough to pump the mixer.

The IF band is set in the 9-21 GHz band fitting specifications of the PREMIER mission (Process Exploration through Measurements of Infrared and millimetre-wave Emitted Radiation). The preliminary design uses separate flip-chip mounted planar Schottky diodes components to perform the two functions. The electrical parameters of the RAL Schottky diode model considered in the simulations for the mixer diodes are an anode diameter of 1.2 μm, a series resistance of 12 Ω, a zero voltage junction capacitance of 8 fF, a saturation current of 2 fA, an ideality factor of 1.2 and a built-in potential of 0.6 V. The parameters for the tripler diode chosen here are an anode diameter of 2.2 μm, a zero voltage junction capacitance of 6 fF, a serie resistance of 4 Ω, a saturation current of 3.10-13 A, an ideality factor of 1.2, a built-in potential of 0.8 V and a breakdown voltage of 8 V.

B. Design methodology

The combined circuit includes six non-linear elements that need to be matched at three different frequencies. The fundamental input source needs to be coupled evenly to the four tripler diodes, the third harmonic generated by these diodes needs to be perfectly coupled to the diodes mixer, and the mixer diodes should be matched optimally at RF frequencies. These conditions have to be fulfilled during a same simulation optimization run.

This type of circuit might present converging issues when performing an harmonic balance simulation with the standard parameters found in ADS software [5]. This is particularly true when it is simulated over a large bandwidth. The methodology for optimizing the circuit in order to reach an optimal conversion loss consists in several steps which have been described in [3]. As a first step, the tripler and mixer diodes

[1] see http://virginiadiodes.com

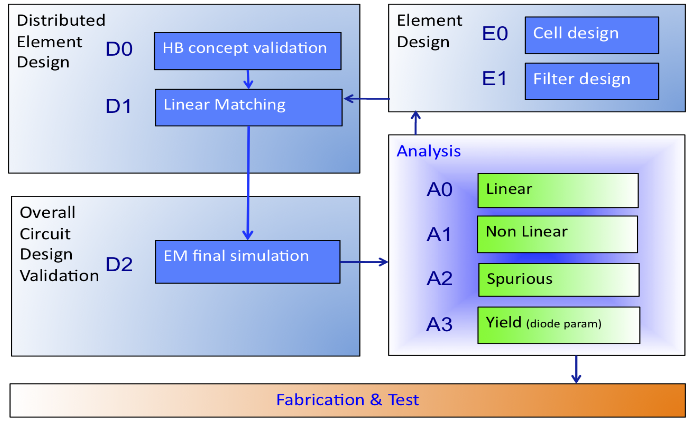

Fig. 2. Design and Analysis methodology for circuits composed of multiple non-linear elements.

optimum impedances are found using the ADS harmonic balance program during two separated simulations. During these simulations, we consider realistic input power conditions (respectively estimated at 20 dBm at multiplier stage input frequency for the tripler diodes and at 2 dBm at LO frequency signal for the mixer diodes). The values of the impedances are found to be Z_{RF} = 53+jx43 and Z_{LO} = 91+jx137 for the mixer diodes and Z_{in} = 37+jx3 and Z_{LO} = 21+jx1 for the tripler diodes. A second step consists in modelling each sub-circuit with a 3D-EM sofware (Ansys HFSS) and using the resulting Sparameter files for an optimization of the distributed circuit in Agilent ADS. The transmissions coefficients are optimized (D1) to reach an ideal of magnitude of 0.7 for the RF input port to the mixer diode ports, 0.5 for the LO input signal to the tripler diode ports and 0.3535 for the tripled signal to each of the mixer diodes. Adapted weighting factors are applied for each of the matching during the optimization. When the non-linear matching reach the desired coupling with an optimal tuning, one can verify the results with a harmonic balance routine.

Despite a good tuning at our frequencies of interest, the large number of non-linear components makes the circuit model complex and susceptible to harmonic mixing products. We will describe the analysis undertaken in order to cross-check the conversion loss results to the circuit linear matching value and its spurious responses.

C. Circuit Analysis

The result of a preliminary design gives the opportunity of better understanding phenomenon occurring in a circuit susceptible to high harmonic mixing products. A 3D EM simulation of the total circuit over the full bandwidth with HFSS is performed. Special care is given to the convergence of the solution at different frequency. Several frequency sweeps are put together in a same S-parameters 11-ports matrix (6 for the mixer and tripler diodes, 4 for the RF and inut signal through waveguides and 1 for the IF output matching).The matrix is then used in an ADS analysis following the three steps given in Fig.2 and decribed hereafter.

1) Overall circuit linear analysis (steps D2 and A0): The linear analysis gives information on the overall circuit matching between the different ports. This result can be compared to the optimization performed in step D1. The matching has slightly shifted from the one found in the distributed model. The RF and input backshorts can be reoptimized for the non linear analysis.

2) Overall circuit non linear analysis (steps D2 and A1): This simulation is performed using the ADS diode model with the parameters given in paragraph A. The previous 11-ports matrix is used to take into account ohmic losses at all frequencies between 100 and 360 GHz (case 1) and 21 GHz and 360 GHz (case 2). The conversion loss is found for case 1 to be a very flat conversion loss between 6 and 7 dB with resonnances at 315 and 345 GHz. When the lower frequencies are taken into account at the mixer diode level (case 2), the conversion loss average falls to a 10 dB level with resonnances around 326 GHz and 345 GHz. The resonnance peaks can be explained by local unbalance seen in the interaction between the tripler diodes or in the magnitude transmission diagram of the input signal overloaded at the center diodes ports and lacking at the extremity diodes ports. The tripler should be reviewed to avoid such effects (step E0). This comparison also highlights the importance of isolating the mixer diode from the frequency band outside the LO band. As a result, a filter element fulfilling this band requirement should be designed (step E1). The spectrum of the fundamental and mixing product signals and their power levels seen by the mixer diodes are given during a spurious analysis simulated at the central frequency point.

3) Overall circuit spurious signal analysis (steps D2 and A2): Spurious signal generation is an issue in non linear circuits. Studies have been conducted to see the effect of parasitic spurious signal at different frequencies coming from bias line or RF port leakage on frequency multiplier output [6]. In our case we consider the spurious generated from intermixing product of the signals inside the circuit, and no outside signal interference is considered. This analysis is particularly useful to determine if unwanted harmonics or mixing product are within the IF band and see the different power levels at frequencies of interest. For this simulations, we have taken a two tone simulation with repectively 1 and 6 harmonics for the RF and input signals and an intermixing order of 7. This minimum order level has been set for accuracy and stability considerations. A significant increase in the signal power level at the fundamental input frequency lands on each of the mixer diodes compared to when ideal isolation is done. This signal appears to be the principal cause of the 3dB degradation of the mixer average performances observed in the non linear analysis.

D. Circuit preliminary performances and main considerations for the final design

The trend of the curve is given with a moving average algorithm to be 10 dB over 12 percent bandwidth for a circuit where the input signal is taken into account at the mixer diodes level.

A second version of the design should consider the effects highligthed during the preliminary design analysis. The main issue is that a good isolation of the signal at the fundamental input frequency propagating in a TEM mode towards the mixer is needed. We note that in similar combined circuit where the isolation is performed by geometric means as in [3] this problem is bypassed by a natural mode selection. The determination of the maximum acceptable power level helps to determine further needed rejection. A study is currently undertaken to integrate a high pass filter with a rejection $\geq$ 10 dB illustrated in Fig.1.

E. Connector Analysis

The combined circuit described in the first part has the advantage of having the possibility of being integrated in a block where one face of the pixel contains the feed aperture, and the opposite face can be dedicated to the local oscillator input and the intermediate frequency output. The attractiveness of this configuration is that a full two-dimensional array (n x m elements, where n and m $\geq$ 2) is possible.

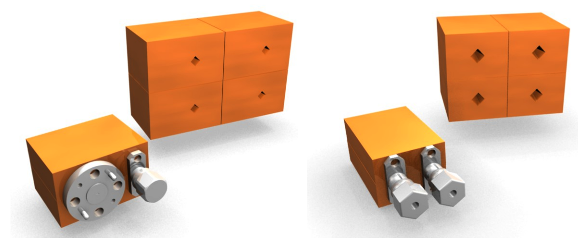

Fig. 3. On-scale pixel block for n x m arrays. The spacing of the feed horn is 22 x 32 mm (left) and 16 x 22 mm (right).

The specifications of future instrument are a beam spacing of a few wavelengths of the array frequency. In this heterodyne Schottky receiver array, the feedhorn spacing is limited by the physical size of the back connector and standard flange. This leads us to difficult packaging constraints as the wavelength of sub-millimeter frequency signal are on the order of one millimeter. A first solution with an array consituted of different connector type could help reducing the beam spacing. An other solution currently beeing studied is using a LO/IF diplexer. Indeed, this option give the possibility to have a pixel with only one connectors at its back face, dedicated to the fundamental E band input and the IF output. This solution could be used to a larger scale if injecting the fundamental input signal through V connectors.

II. Conclusion

The single pixel receiver block described here includes a combined circuit tripler / sub-harmonic mixer circuit at 330 GHz. The large number of non-linear components makes the circuit model complex and susceptible to harmonic mixing products. The design methodology is described in order to enlight the effect of unwanted signal landing on the mixer, and local unbalance at multipler level. Predicted performance of a preliminary design suggests a DSB conversion loss with an average value of 10 dB over 12 percents bandwith with a 20dBm input power at E band. An analysis of packaging constraints is also provided since the spacing between two horn antennas is limited by the physical size of the local oscillator and IF connectors on the back face of the pixel.

ACKNOWLEDGMENT

This work is being conducted with the ESA program ESA RFQ3-12346/08/NL/ST. The authors would like to thank Thibault Vacelet for drawing the scaled version of the mono-pixel concept with different connector types.

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