A Hybrid Bipolar Wideband VCO with Linearized Tuning Behaviour for a New Generation TTC Transponder

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***Abstract* — This paper presents a wideband voltage-controlled oscillator (VCO) using hybrid technology based on bipolar transistors for a new generation TTC Transponder.**

The VCO is based on microstrip three-pole combline bandpass filter with just one varactor diode. The bandpass filter is embedded into the feed-back loop to treat as a frequency stabilization element. The VCO delivered 4.63 dBm maximum output power at 3.4 GHz with a current consumption of 17.4 mA for a supply voltage of 3 V and it has a tuning range achieved from 600 MHz being the frequency range from 2.8 GHz to 3.4 GHz. The developed VCO with three pole combline filter is experimentally demonstrated at 3.4 GHz with a phase noise of -126 dBc/Hz at 1 MHz offset frequency. In addition, over this frequency range, all the phase noises measured at 1 MHz are better than -118 dBc/Hz.

***Keywords* — Combline filter, phase noise, voltage-controlled oscillator (VCO)**

I. Introduction

This work was developed as part of a research project. The project`s goal is the manufacturing of a frequency converter for satellite communications using low cost building blocks. The system implements a frequency conversion of a modulated wave from S-Band to X-Band.

Microwave oscillator are the heart of all RF and microwave systems from wireless communications, radar and navigation, military and aerospace to vital test equipment. Voltage controlled oscillators (VCO) represent the most common form of oscillators that tune across a band of frequencies specific to applications. VCOs have come a long way from the vacuum tube based components of 85 years ago to present fully hybrid circuits. Stand- alone VCOs are commercially available in various SMT packages, hybrid coaxial modules, as well as part of a higher-level mixed-signal ASICs. Improvements in VCO technology have continued throughout that time, yielding ever-smaller sources with enhanced performance.

The voltage controlled oscillators (VCO) are one of the most important building blocks that communications transceivers are based. The main properties to consider are the phase noise, the tunning range, and the output power. Between these, the most demanding are the phase noise and the tunning range, so the correct choice of the manufacturing technology and the topology will be crucial in the final results [1], [2].

This paper describes a low phase noise and voltage controlled oscillated manufactured in hybrid technology. The purpose is long term technological development, focused on the research of new technologies and techniques for telecommunications satellites and terrestrial and user equipment. This process is suitable for the realization of VCOs with low phase noise due to its inherent low noise 1/f, its reliable manufacturing process and its low cost.

In addition to the importance of getting a low phase noise and good tunning range, other important objective consist of making the circuit compact with small dimensions and low consumption, which are design drivers for any on-board equipment.

II. Circuit Design

The VCO topology is based on a Colpitts. This oscillator configuration has been chosen due to its good impulse sensitivity characteristic as described Lee and Hajimiri [3], what is essential to get high quality factor and therefore to get low phase noise. In addition, the Colpitts configuration offers a good behaviour in this frequency band from 2 GHz to 4 GHz.

The VCO has been designed taking into account several aspects, the first one the use of a bipolar transistor in order to have a better phase noise characteristic. The Fig 1 shows the VCO core.

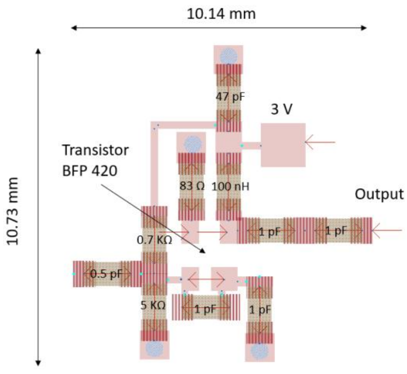

Fig. 1. Hybrid VCO core design.

The bipolar transistor chosen was the BFP420 low noise silicon bipolar RF transistor, which is quite used in oscillators up to 10 GHz. The BFP420 bipolar transistor is biased at $Vcc = 3\,V$ with a collector current consumption of 17.4 mA.

Another important aspect that has been studied was the resonator based on DH7600 series varactors with its own polarization network. The varactor diode cathode voltage varies from 0 V to 5 V, and the varactor diode anode from 0 V to -5 V getting a potential difference between the terminals of the varactor diode from 0 V to 10 V [9].

As a resonator a three-pole combline bandpass filter was developed in this project that is composed of three coupled lines. The varactor diode is attached to the filter and provide a capacity range what change the filter line length and allows to select the frequency band. The filter dimensions are indicated in the Fig 2. The VCO phase noise depends on the resonator quality factor. If the quality factor is high, the resonance will be more "sharp" and with the low phase noise sidebands. Furthermore, microstrip lines separation must be large enough (0.95 mm) to get some weak coupling that allows for the VCO feedback and avoid losing output power.

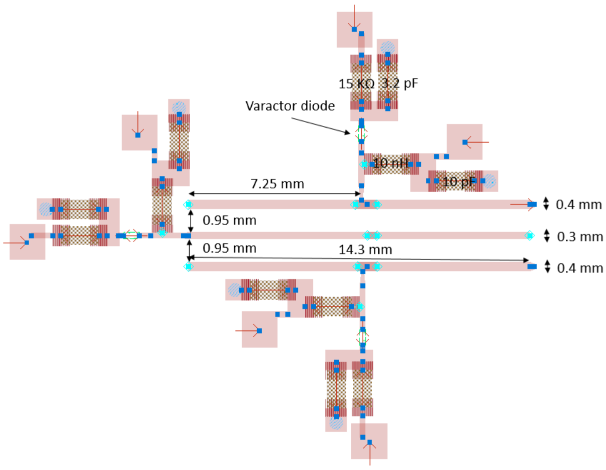

Fig. 2. VCO resonator design. Three pole combline filter and varactor polarization network

At first, the resonator was composed of three varactor diodes for having a symmetric response. However, the oscillation criteria based the auxiliary source [10] shows that it is only necessary to use the varactor diode located in the upper filter line to meet the criterion in a bigger frequency band. The varactor diode located in the medium and lower lines of the filter just meet the criterion in a narrow frequency band. Then to reduce costs, it is used one varactor diode attached on the top microstrip line of the trisection filter between the open-circuited terminal and the collector to provide a capacitance tuning range of 0.9 – 5.2 pF to control the oscillation frequency.

The Fig 3 shows the small signal simulation results applying the oscillation criteria [10].

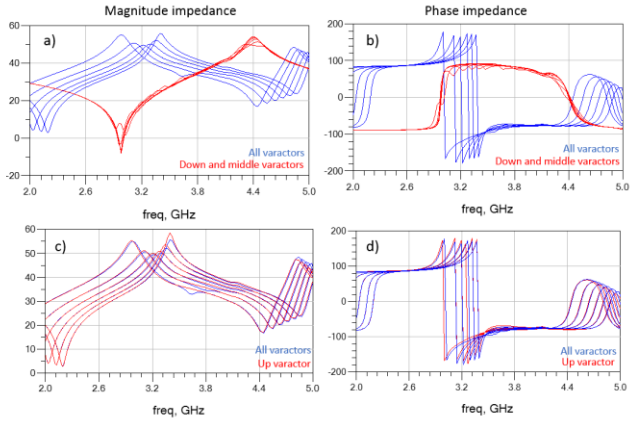

Fig. 3.(a) Magnitude comparison using all varactor diodes with down and middle varactor diodes, (b) phase comparison using all varactor diodes with down and middle varactor diodes, (c) magnitude comparison using all varactor diodes with up varactor diode, and (d) phase comparison using all varactor diodes with up varactor diode.

According to the "Barkhausen oscillation criteria", the loop gain of the VCO must be greater than unity and the total loop phase should satisfy 0º. Then, to design the VCO from 2.82 GHz to 3.42 GHz the length of the transmission line is especially important to meet this criterion. The physical dimensions of the connecting line are shown in the Fig 4.

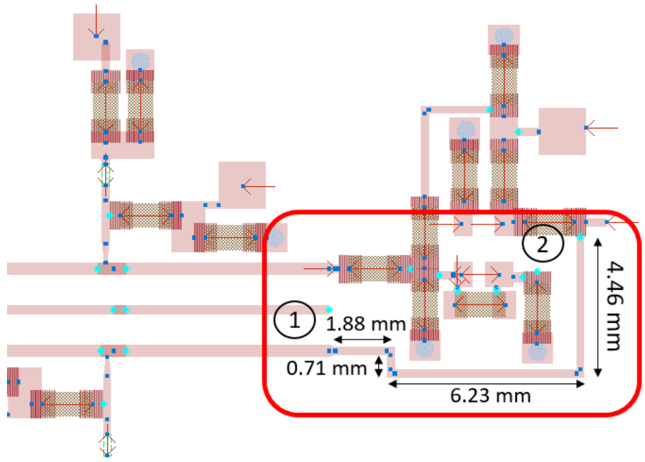

Fig. 4. Length of the transmission line to achieve the "Barkhausen oscillation criteria"

The VCO output is connected to an output buffer, which is based on a base common amplifier. This buffer is necessary to isolate the VCO from any load variation and to provide the necessary output power.

III. Measurement Results

The VCO has been measured using the Agilent spectrum analyser with the Agilent PSA E4448A model.

For the VCO manufacturing it is used the RO4003C substrate, with a dielectric constant (ϵ_r) of 3.38, a thickness of 0.305 mm, and loss tangent of 0.0021. The VCO occupies an area of approximately 19 mm x 34 mm. Most of area is taken up by the resonator, but it can be reduced because just one varactor diode will be used.

The final result of the VCO design is shown in Fig 5 and the VCO photograph in the PCB is shown the Fig 6.

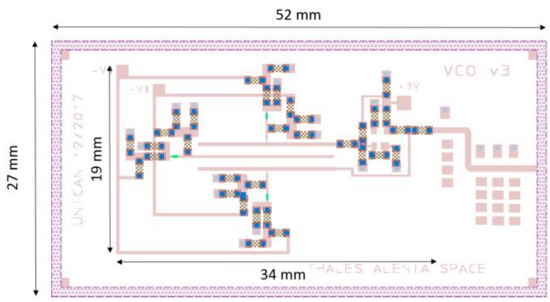

Fig. 5. Hybrid VCO Physical dimensions

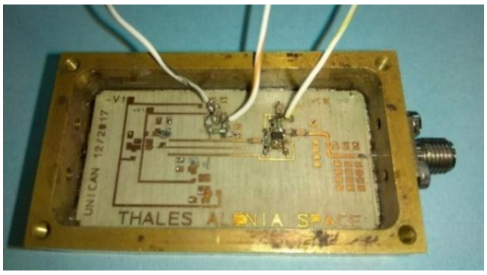

Fig. 6. Circuit photograph of the voltage controlled oscillator designed

The measured oscillation frequency (f_o) and the output power are shown in the Fig7 as a function of the tuning voltage (V_t). As shown in Fig 7, the available frequency tuning range of the developed VCO is from 2.82 GHz to 3.42 GHz as V_t changed from 0 V to 10 V with a 19.2% bandwidth.

The VCO measured output power varies from 2.2 dBm (minimum value) to 4.65 dBm to 3.42 GHz.

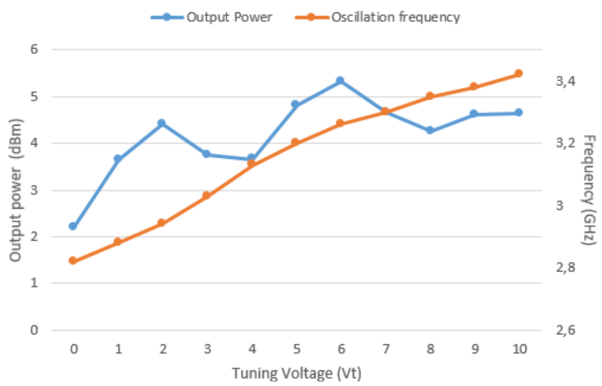

Fig 7. Measured output power and oscillation frequencies of the developed wideband VCO

The next Fig 8 shows a comparison between the measured oscillation frequency and the simulated oscillation frequency. However, it can be observed that there is a variation from 200 MHz between the measured oscillation frequency and the simulated oscillation frequency. It means that any little variation between the varactor diode model and its real behaviour, can lead to a frequency shift as it shown in simulation. The best solution to the problems of the simulation models is realize a varactor diode measure and extract a behavioural model that can be used in future simulations. The simulation results have been obtained applying a method based on auxiliary sources used for stability analysis using harmonic balance [11].

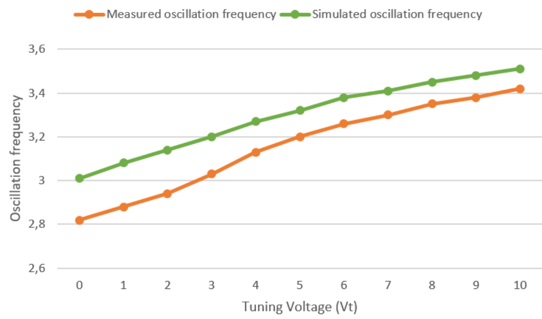

Fig. 8. Comparison between the measured oscillation frequency and simulated oscillation frequency.

The phase noise measured was also realized with the spectrum analyser. The Fig 9 shown a close in spectrum with the VCO tuned at the upper band (3.42 GHz) and the Fig 10 shows the phase noise measurements versus the tuning voltage. Over the frequency tuning range, all the measured phase noises at 1 MHz offset frequency are better than -118 dBc/Hz. The best phase noise at 1 MHz offset frequency can be achieved at 3.42 GHz, and it is -126 dBc/Hz. Here, the measured phase noises become better as the oscillation frequency is tuned to the higher frequency band. Also, it is realized measurements at 20 KHz offset frequency where the best phase noise measured is -90 dBc/Hz at 3.35 GHz. The Fig 11 shows the phase noise measurements at 20 KHz offset frequency.

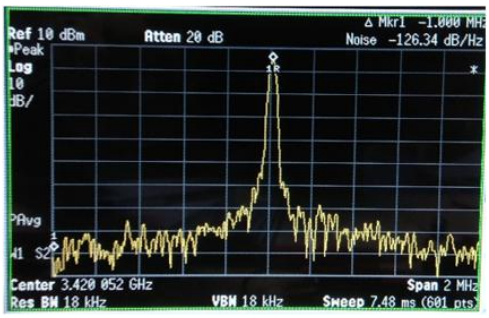

Fig. 9 Output spectrum of 2 MHz span at upper band

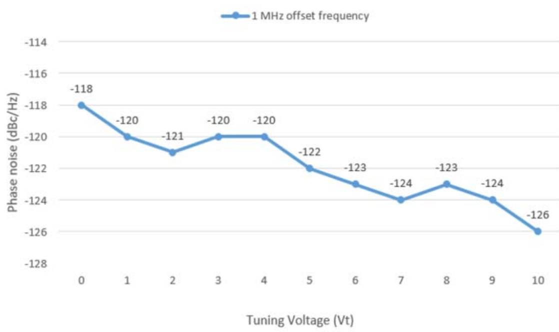

Fig. 10. Measured phase noise at 1 MHz frequency offset from the carrier versus tuning voltage

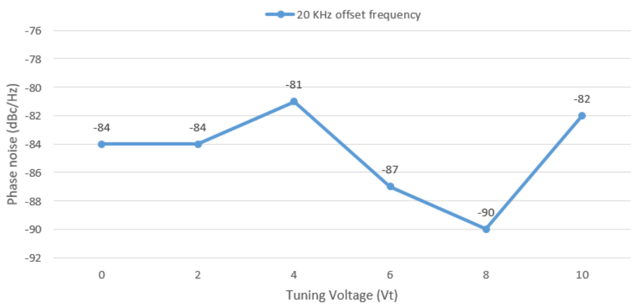

Fig 11 Measured phase noise at 20 KHz frequency offset from the carrier versus tuning voltage

Referred to the wideband output spectrum illustrated in Fig 12, this VCO has a second harmonic suppressions of -14.8 dBc and -19.9 dBc for the third harmonic.

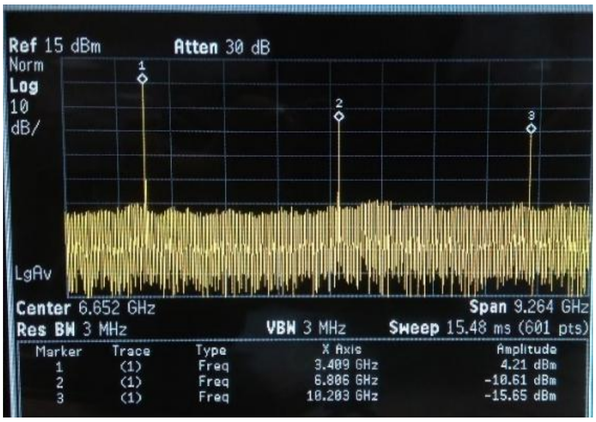

Fig. 12. Measured wideband output spectrum of the developed hybrid VCO

The performance comparison between published VCOs and this study are summarized in Table 1. Although the VCO in [4] has a better phase noise at 3.4 GHz, the proposed VCO in this paper has a bigger tuning range. The VCO in [6] has a better tuning, but it is necessary to consider that operates on a lower frequency band and it is using two more varactor diodes what increase the complexity.

Table 1. Comparison between published VCOs

	Frequency (GHz)	Tuning range (%)	Phase noise (dBc/Hz)	Phase noise normalized at 3.4 GHz	FOM (dBc/Hz)	Offset freq. (Hz)
[4]	2.1	1.6	-138	-134	-203	1 M
[5]	5.8	11	-100	-105	-159	1 M
[6]	2.2	54.8	-134	-100	-158	1 M
This work	3.4	19.2	-126	-126	-179	1 M

IV. Conclusion

A voltage controlled oscillator has been designed with low phase noise, with low complexity and wide tuning range for this frequency band and enough output power for space applications using hybrid technology. To optimize the phase noise characteristic and to reduce costs, a microstrip three-pole combline resonator has been used with a high quality factor, as well as single varactor diode to reduce the parasitic elements. The VCO delivered a phase noise from -90 dBc/Hz at 20 KHz and -126 dBc/Hz at 1 MHz offset frequency, an output power from above 4 dBm at a current consumption lower than 18 mA, an oscillation frequency from 3.42 GHz and 600 MHz bandwidth (19.2%). The highest harmonic level was measured to be -14.8 dBc. The final area was 19 mm x 34 mm and the substrate used RO4003C.

Acknowledgment

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