A Quenchable GaAs HBT X-Band VCO for Switched Band Synthesizer Architectures

K.W. Kobayashi, D.M. Smith, C.P. Kau, A.K. Oki, A.K. Sharma, B.R. Allen, and D.C. Streit

TRW Electronics Systems and Technology Division
One Space Park, Redondo Beach, CA 90278

ABSTRACT

Here we have achieved the lowest phase noise reported for an HBT VCO at X-band. The VCO employs an off-chip quarter-wave open stub microstrip resonator fabricated on a 50 mil quartz substrate and a shunt-varactor diode for frequency tuning. At a center frequency of 8.9 GHz, the VCO achieves -103 to -105 dBc/Hz at 100 KHz over a tuning bandwidth of 140 MHz (1.6%). By reducing the unloaded Q of the microstrip resonator, a 770 MHz tuning bandwidth (8.6%) can be achieve with a phase noise ranging from -98.5 to -100.5 dBc/Hz. Without a tuning varactor, a record minimum phase noise of -112 dBc/Hz was achieved at a center frequency of 8.3 GHz which benchmarks the lowest reported phase noise achieved for an HBT oscillator at X-band. The HBT VCO MMIC features a monolithically integrated PIN diode quench circuit which enables the VCO to be used in switch-band synthesizer applications.

Introduction

HBT device technology has been proposed for low phase noise VCO applications due to their low 1/f noise compared to MESFETs, and microwave to millimeter-wave cut-off frequencies. Several early HBT VCO developments have already demonstrated superior phase noise performance compared to MESFET VCOs and comparable performance to silicon bipolar based VCOs at C- and Ku- band frequencies [1], [2]. Others have shown that HBT VCOs offer additional performance advantages in terms of DC-RF conversion efficiency [3], [4], [5]. More recent literature has focused on demonstrating monolithic HBT VCO varactor tuning capability as well as higher frequency operation using advanced HBT device structures [6]-[18].

This work focuses on the development of a low phase noise X-band quenchable HBT VCO intended for use in a switched band frequency synthesizer architecture such as the one shown in Fig. 1. A previously reported quenchable VCO has been demonstrated in MESFET technology which uses a passive

Block Diagram of Switch Band VCO Architecture

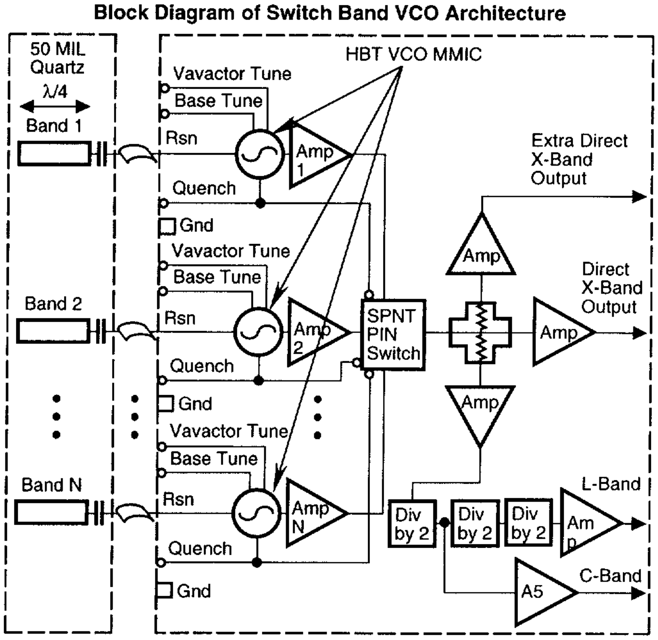

Fig. 1 Schematic of a proposed multi-VCO switched-band analog synthesizer architecture which employs the Quenchable HBT VCO.

FET switch for providing oscillation quenching[19]. In the present work, a PIN diode switch is integrated with an HBT VCO to provide the quenching capability. The quench capability allows one to select from a bank of HBT VCOs covering different frequency bands in order to provide a continuously wide frequency synthesizer tuning band. This implementation relaxes the tuning bandwidth required of each of the VCOs and allows the implementation of high Q resonators with narrow bands in order to achieve lower phase noise.

Fig. 2 shows the phase noise performance of previously reported HBT-based VCOs [1]-[4], [6], [8]-[12], [14]-[18]. This plot also shows unpublished TRW hybrid VCO performance. This work benchmarks the lowest phase noise so far recorded at X-band for an HBT oscillator with a record -112 dBc/Hz phase noise at 100 KHz offset at 8.3 GHz. This phase noise is comparable to previously reported HBT DRO performance [1], [4], [6], [18] when normalizing the phase noise to center

0-7803-3360-8/96/$5.00 © IEEE IEEE 1996 Microwave and Millimeter-Wave Monolithic Circuits Symposium

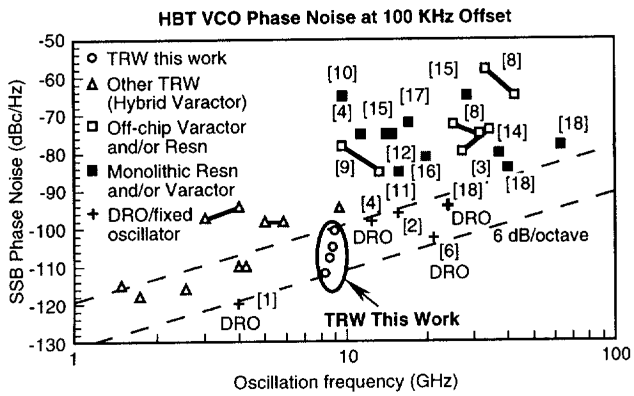

Fig. 2 Summary of previously reported HBT VCO phase noise performance.

frequency using a 6 dB/octave frequency relationship represented by the dashed lines. Other flavors of our VCO illustrate wider tuning bandwidths while still achieving state-of-the-art phase noise for HBT VCOs at X-band.

HBT Technology

An AlGaAs/GaAs HBT MBE profile has recently been developed to achieve low frequency 1/f noise characteristics. The profile incorporates a 20% Al composition emitter which is linearly graded from the emitter to the base. The low frequency noise of the 20% Al graded HBT has demonstrated significant improvement in performance over a conventional 30% AlGaAs HBT graded profile, and comparable performance to InGaAs-InP-based HBTs[20]. The 20% Al graded HBTs have exhibited well behaved noise characteristics over temperature as well.

Quenchable HBT VCO Design

A schematic of the HBT MMIC VCO with external resonator is shown in Fig. 3. The active HBT VCO circuit employs a 2x10 μm^2 quad-emitter common-collector HBT which is nominally biased at 8 mA. A common-collector configuration is used for its broad band instability characteristics. A shunt capacitor Ce on the emitter is used to tune the region of negative resistance as seen looking into the base of Q1. An emitter degeneration resistor Ree is used to help bias Q1 as well as inhibit up-conversion of low frequency noise onto the skirts of the desired RF tone. *Oscillation quench* is realized by integrating a monolithic PIN diode in series with the collector of the HBT. By switching the diode off (open) and on (short), the oscillation can be quenched and unquenched while avoiding undesirable thermal drift and settling time associated with biasing the transistor on and off as a means of quenching. This is a major concern when trying to employ a bank of oscillators to construct a wide tuning band using a switched-band synthesizer scheme.

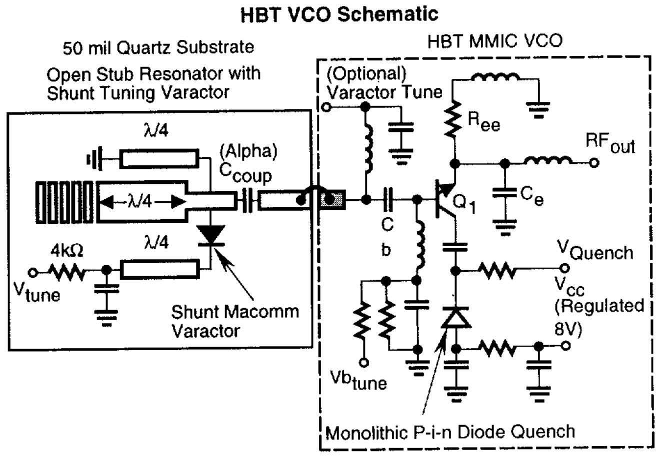

Fig. 3 Schematic of the HBT MMIC VCO and external microstrip resonator.

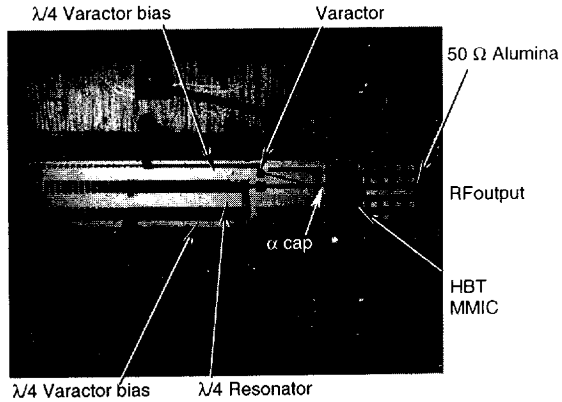

Fig. 4 Photograph of the hybrid/MMIC HBT VCO.

An off-chip microstrip open stub resonator fabricated on a 50 mil (low dielectric) quartz substrate is integrated with the MMIC to realize a high resonator Q. The open stub resonator is 5 mil wide and slightly over a quarter-wave in length to provide a high inductive reactive impedance slope to the HBT MMIC. The open stub resonator is coupled to the base of the VCO through a series off-chip 0.2 pF Alpha coupling capacitor and an on-chip 0.25 pF coupling capacitor. The effective coupling capacitance is critical in determining the effective loaded Q of the resonator.

Voltage controlled frequency tuning is realized using a 0.6 pF shunt Macomm varactor diode. This shunt varactor configuration was found to achieve lower phase noise with modest tuning bandwidths compared to a series varactor configuration. In the shunt varactor scheme, the tuning bandwidth and associated phase noise performance was adjusted by placing the varactor at various positions along the resonator line.

Fig. 4 shows a photograph of the hybrid/MMIC HBT VCO. The HBT MMIC chip is 1.4x1.5 mm ^{2} and contains the active HBT device and matching structures as well as dc bias and PIN diode quench networks. A 50 mil quartz resonator is coupled

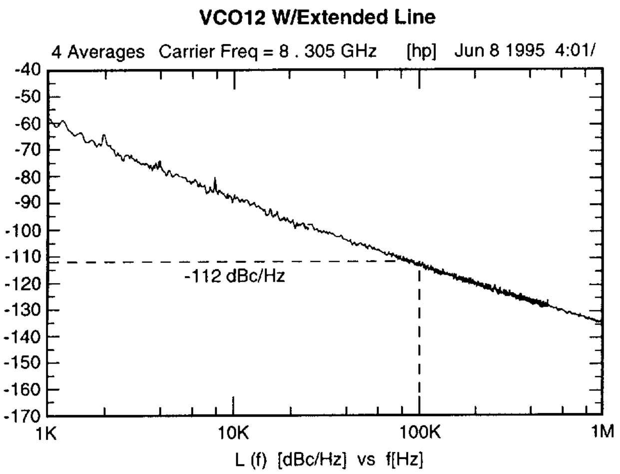

Fig. 5 Phase noise versus offset frequency at 8.3 GHz taken from a phase discriminator phase noise test setup. Varactor-less configuration.

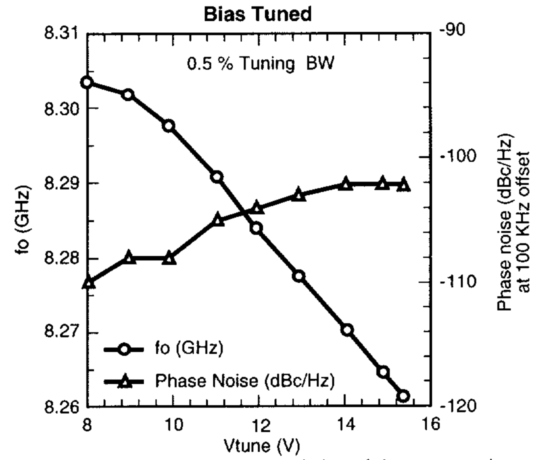

Fig. 6 Phase noise and tuning characteristics of the varactor-less VCO-resonator.

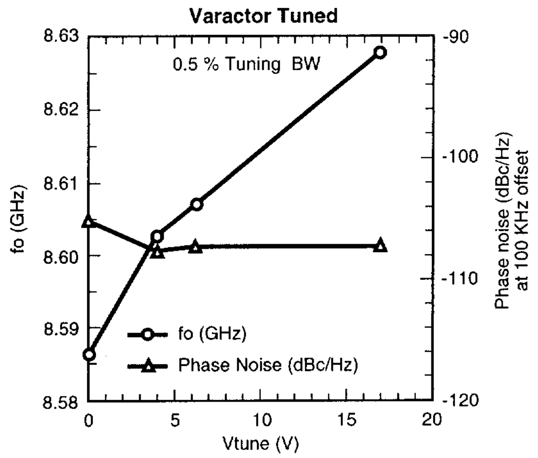

Fig. 7 Phase noise and tuning characteristics of the shunt-varactor VCO-resonator.

to the MMIC through a discrete coupling capacitor which is mounted on the quartz substrate. The base and varactor tuning lines as well as the Vcc supply line, are heavily filtered in order to inhibit the injection of noise from the bias and control lines. The complete fixtured VCO is 5x4x1.5 cm ^{3}.

VCO Measurements

The phase noise of the VCO without the shunt varactor was first measured in order determine the minimum phase noise without the Q-factor loading effects of the varactor. A collector bias current of 6-8 mA was found to give the best performance. Fig. 5 shows a plot of phase noise versus offset frequency at 8.3 GHz taken from a phase noise discriminator test setup. At 10 KHz and 100 KHz offsets the phase noise is -88 dBc/Hz and -112 dBc/Hz, respectively. This phase noise is comparable to previously reported HBT DRO performance. In this "varactor-less" configuration, a 42 MHz or 0.5% tuning range was achieved by varying the base bias voltage and is illustrated in Fig. 6. A phase noise of -102 to -109.9 dBc/Hz at 100 KHz offset was measured directly from a spectrum analyzer over this tuning range. The spectrum analyzer noise floor is -110 dBc/Hz.

With a shunt varactor integrated with the microstrip resonator, a phase noise of -105.2 to -107.7 dBc/Hz at 100 KHz offset was achieved over a 43 MHz tuning band. These tuning characteristics are illustrated in Fig. 7 and were taken at a center frequency of 8.6 GHz. The varactor tuning characteristic illustrates less phase noise variation over the same tuning bandwidth compared to the "varactor-less" bias-tuned measurement of Fig. 6, with less than 3 dB variation.

Since it was determined that the resonator Q dominates the bandwidth and phase noise performance of our VCO, the tuning bandwidth was increased by reducing the loaded Q of the resonator. The loaded Q of the resonator was reduced by 1) increasing the coupling between the MMIC and the quarter-wave microstrip resonator and, 2) reducing the unloaded Q-factor of the microstrip resonator, independently. Of course these changes increase the tuning bandwidth at the expense of higher phase noise. Fig. 8 shows the tuning characteristics of the VCO for the increased resonator coupling case which was obtained by removing the small 0.2 pF Alpha coupling capacitor. Over the full varactor tuning range, the VCO now achieves 140 MHz of tuning bandwidth and a phase noise of -103.3 to -105 dBc/Hz at 100 KHz offset from 8.5 GHz. This is a factor of 3 improvement in tuning bandwidth however, at the expense of 2-2.5 dB increase in phase noise. On the other hand, by replacing the small 0.2 pF Alpha coupling capacitor and reducing the unloaded Q-factor of the microstrip line by increasing its width from 5 mils to 20 mils (this reduces the reactive impedance slope of the line), a much wider tuning bandwidth of 770 MHz was obtained with a phase noise of -98.5 to -100.5 dBc/Hz at 100 KHz offset (from 9 GHz) and is shown in Fig 9. This corresponds to an 8.6 % tuning bandwidth. A much greater trade-off between phase noise and

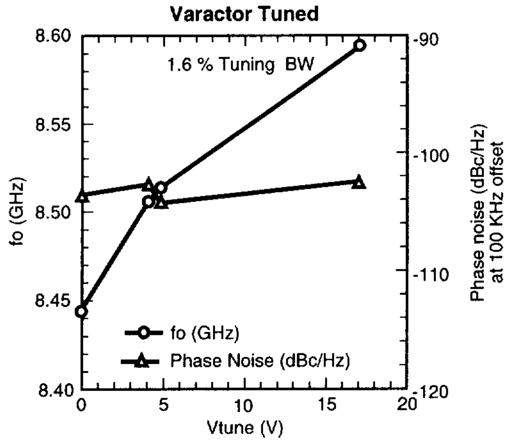

Fig. 8 Phase noise and tuning characteristics of the shunt-varactor VCO with the 0.2 pF Alpha series coupling cap replaced by a shorted line.

bandwidth exists here because the unloaded resonator Q-factor dominates the overall loaded Q-factor of our VCO configuration.

Table 1 gives a summary of the VCO performance for the various resonator configurations. The output power of these VCOs range from -12 to -16 dBm. The "varactor-less" or bias-tuned configuration of this work achieves comparable phase noise to previously reported HBT DROs as previously stated. The varactor-tuned VCOs have lower Q's and higher phase noise responses because of the losses associated with the varactor. The varactor-tuned VCOs of this work resulted in tuning bandwidth flavors of 0.5%, 1.6%, and 8.6% with corresponding phase noise which are the lowest reported for HBT-based VCOs at X-band.

Conclusion

A quenchable X-band HBT VCO employing a high Q quartz microstrip resonator and varactor tuning demonstrated state-of-the-art HBT phase noise performance. The low phase noise HBT VCO can be implemented in a multi-VCO switched band architecture for realizing a wide synthesizer tuning bandwidth. Furthermore, because of the multi-functional properties of HBTs, an inexpensive high performance VCO MMIC integrating other loop functions such as frequency dividers, switches and buffer amplifiers, can ultimately be produced and made available as a low cost, high performance off-the-shelf MMIC component for synthesizer applications.

Acknowledgment

The authors would like to acknowledge the sponsorship of the Naval Command Control and Ocean Surveillance Center, RDTNE Division Detachment, Warminster, PA. Technical points of contact at code 341 were Dean Nathans, Rick Werrell, and Busey Collier. Funding was provided by the Office of Naval Research and the Defense Support Project Office.

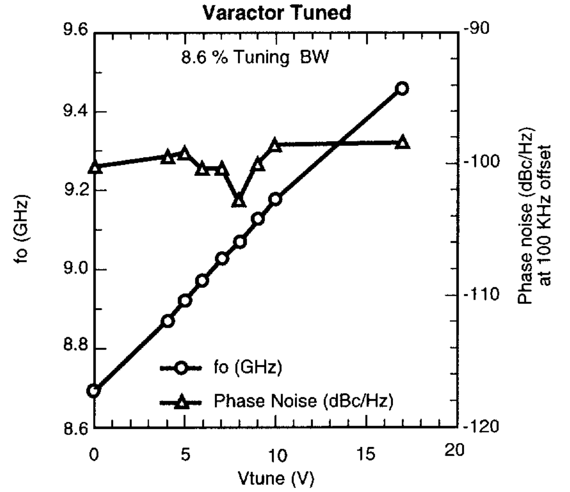

Fig. 9 Phase noise and tuning characteristics of the shunt-varactor VCO with a reduced unloaded Q microstrip resonator (w=5 mil--> w=20 mil).

Table 1. Summary of VCO Performance

Resonator Configuration (50 Mil Quartz)	fo (GHz)	Phase Noise (dB/Hz) @ 100 KHz Offset	Tuning BW (MHz)
λ/4 Open Stub, W = 5 mil With 0.2 pF Coupling Cap No Varactor	8.3 8.3	-112* -102 to -109.9	— 42 (Bias tuned)
λ/4 Open Stub, W = 5 mil With 0.2 pF Coupling Cap With Shunt Varactor	8.6	-105.2 to -107.7	43
λ/4 Open Stub, W = 5 mil Without Coupling Cap With Shunt Varactor	8.5	-103.3 to -105	140
λ/4 Open Stub, W = 20 mil With 0.2 pF Coupling Cap With Shunt Varactor	9.0	-98 to -100.5	770

*Phase Discriminator Test Set Up

References

[1] K.K. Agarwal, 1986 *IEEE MTT Symp. Dig.*, Baltimore, Maryland, pp. 95-98.
[2] N. Hayama, et.al., *1988 MTT Symp. Dig.*, New York, NY, pp. 679-682.
[3] M.E. Kim, et.al., *1988 IEEE GaAs IC Symp. Dig*, Nashville, Tenn., pp. 74-77.
[4] M.A. Khatibzadeh, et.al., 1989 *IEEE GaAs IC Symp. Dig.*, San Diego, CA, pp. 11-14.
[5] K.W. Kobayashi, et.al., *1993 IEEE MMWMC Symp. Dig.*, Atlanta, GA, pp. 85-88.
[6] U Guttich, et.al., in *1993 Int. Symp. GaAs and Related Compounds*, Freiburg, Germany, pp.15-20.
[7] M. Madihian, et.al., *1988 IEEE GaAs IC Symp. Dig.*, Nashville, Tenn., pp. 113-116.
[8] D.M. Smith, et.al., *1989 IEEE MTT Symp. Dig.*, Long Beach, CA, pp. 78-81.
[9] A.K. Oki, et.al., *1990 GOMAC Dig.*, Nov. 1990, pp. 101-104.
[10] N.-L. Wang, et.al., *1991 GaAs IC Symp. Dig.*, Monterey, CA, pp. 255-258.
[11] Y. Yamauchi, et.al., *1991 IEEE GaAs IC Symp. Dig.*, Monterey, CA, pp. 259-262.
[12] A. Adar et.al., *1991 IEEE MMWMC Symp. Dig.*, Boston, MA, pp. 73-76.
[13] E.A. Sovero, et.al., *1992 IEEE GaAs IC Symp. Dig.*, Miami, FL, pp. 305-308.
[14] U. Guttich, et.al., *1994 IEEE MMWMC Symp. Dig.*, San Diego, CA, pp. 165-168.
[15] H. Blanck, et.al., *1994 IEEE MMWMC Symp. Dig.*, San Diego, CA, pp. 161-164.
[16] L. Tran, et.al., *1995 IEEE MMWMC Symp. Dig.*, Orlando, FL, pp. 101-104.
[17] K.W. Kobayashi, et.al., *IEEE Microwave and Guided-Wave Lett.*, vol. 5, no. 9, Sept. 1995, pp. 311-312.
[18] H. Wang, et.al., *1995 IEEE GaAs IC Symp. Dig.*, San Diego, CA, pp. 263-266.
[19] G. Dietz, et.al., "A 10-14 GHz Quenchable MMIC Oscillator," in *1991 IEEE MTT Symp. Dig.*, Boston, MA, pp. 23-26.
[20] J. Cowles, et.al., *1995 IEEE MTT Symp. Dig.*, Orlando, FL, pp. 689-692.