Total Dose Tolerance of Monolithic Millimeter-Wave Transceiver Building Blocks Implemented in 200 GHz SiGe Technology

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Abstract— **This paper presents the first experimental results on the effects of 63.3 MeV proton irradiation on 60 GHz monolithic point-to-point broadband space data link transceiver building blocks implemented in a 200 GHz SiGe HBT technology. A SiGe low-noise amplifier and a SiGe voltage-controlled oscillator were each irradiated to proton fluences of 5.0×10^{13} p/cm^2. The device and circuit level performance degradation associated with these extreme proton fluences is found to be minimal, suggesting that such SiGe HBT transceivers should be TID-tolerant for space applications, without intentional hardening at either the device or circuit level.**

Index Terms: Proton irradiation, silicon-germanium (SiGe), heterojunction bipolar transistor (HBT), transceiver, low-noise amplifier (LNA), voltage-controlled oscillator (VCO), millimeter-wave.

I. INTRODUCTION

An important emerging market for millimeter-wave (mm-wave = > 30 GHz) IC technologies lies in very high bandwidth (> 1 Gb/sec) point-to-point communications data links [1][2]. Traditionally, discrete microwave integrated circuits implemented in III-V technologies (GaAs and/or InP) have been combined to realize mm-wave transceiver modules because they offered significant performance advantages at mm-wave frequencies over Si technologies [3]-[5]. Unfortunately, such transceiver modules are typically power hungry, large, heavy and hence costly [6][7]. Clearly, for space applications of such mm-wave data links, achieving low power, small size, light weight, and low cost are essential requirements in addition to maintaining acceptable performance and high reliability. As will be demonstrated, an alternative IC technology based on silicon-germanium (SiGe) alloys can potentially fulfill these requirements [8][9].

SiGe heterojunction bipolar transistor (HBT) technology utilizes bandgap engineering techniques to dramatically improve transistor-level performance while simultaneously maintaining strict compatibility with conventional silicon (Si) manufacturing [10]. The evolution of SiGe technology is evolving very rapidly, and has today reached a point where SiGe HBT technology is of comparable performance with the best-of-breed III-V technologies. With the recent announcement of third-generation SiGe HBTs having peak cutoff frequency (f_T) above 200 GHz [11] and fourth-generation technology having peak f_T above 300 GHz [12], the application space for SiGe HBT technology has further broadened from a variety of analog and radio frequency (RF) applications to now include monolithically integrated mm-wave communications systems. SiGe HBT technology thus combines III-V like device performance with the high integration, high yield, and hence low cost associated with Si to facilitate system-on-a-chip solutions. In addition, SiGe HBTs have also been shown to be robust with respect to total dose irradiation without any additional costly radiation hardening (SEU mitigation remains under investigation). With these attributes, SiGe HBT technology promises to provide high performance, high reliability, small size, light weight, and low cost required for monolithic mm-wave transceivers for space link applications.

A monolithic mm-wave transceiver capable of operating in the 60 GHz ISM band is being developed using third-generation 200 GHz SiGe HBT technology. In addition to short-range terrestrial wireless broadband applications, such a transceiver could also find application in inter-satellite communication links. This paper presents, for the first time, experimental results on the effects of proton irradiation on critical building blocks for such a 60 GHz monolithic mm-wave transceiver.

II. PROCESS TECHNOLOGY

The SiGe HBT technology investigated in this paper is the IBM SiGe 8T technology with 207 GHz peak f_T and 285 peak maximum oscillation frequency (f_{max}) [11]. It features copper interconnects with a thick top layer aluminum metallization and a full suite of passive elements. This advance in the SiGe state-of-the-art to 200 GHz transistor performance was only achieved by radically altering the structure of previous SiGe HBT design points. The present technology employs a novel, reduced thermal cycle, "raised extrinsic base" structure, and utilizes conventional deep and shallow trench isolation, an *in-situ* doped polysilicon emitter, and an unconditionally stable, 25% peak Ge, C-doped, graded UHV/CVD epitaxial SiGe base. The device structure has been scaled laterally to 0.12 μm emitter stripe width in order to minimize base resistance and thus improve the frequency re-

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TABLE I
SUMMARY OF THE SIGE HBT PARAMETERS

W_E	0.12 μm
Peak β	400
Peak f_T	207 GHz
Peak f_{max}	285 GHz
BV_{CEO}	1.7 V
BV_{CBO}	5.5 V

sponse and noise characteristics. Such a raised extrinsic base structure facilitates the elimination of any out-diffusion of the extrinsic base, thereby significantly lowering the collector-base junction capacitance. This SiGe HBT technology has not been intentionally radiation-hardened in any way. A schematic cross-section of the SiGe HBT is shown in Figure 1. Typical transistor parameters are summarized in Table I.

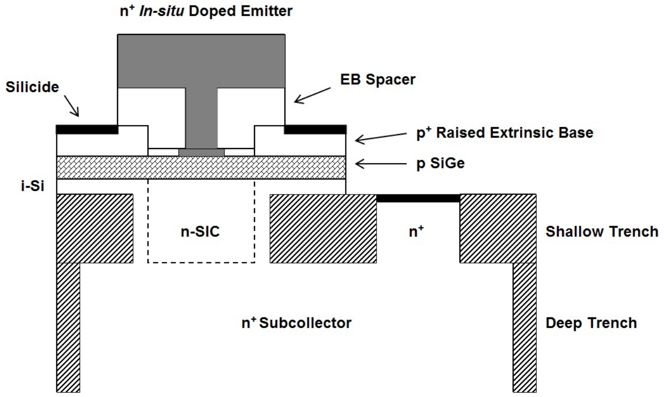

Fig. 1. A schematic cross-section of the 200 GHz SiGe HBT.

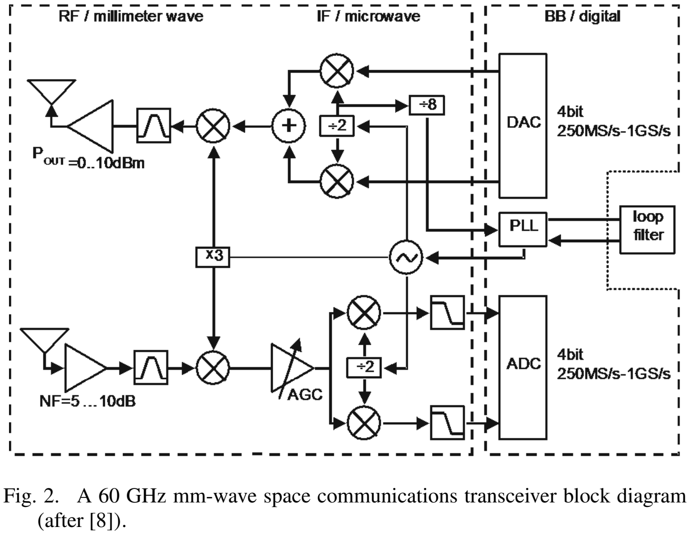

Fig. 2. A 60 GHz mm-wave space communications transceiver block diagram (after [8]).

III. EXPERIMENT

The goal of this work was to carefully assess the impact of radiation exposure on actual 60 GHz monolithic mm-wave transceiver building blocks implemented in 200 GHz SiGe HBT technology, and use an additional transistor-level radiation experiment to better understand the observed circuit response. A 60 GHz mm-wave transceiver block diagram is shown in Figure 2. Two key components are chosen for this study: one is the low-noise amplifier (LNA), which is used to amplify the received signals while adding minimal noise; the other is the voltage-controlled oscillator (VCO), which is used to generate local oscillator (LO) signals for up- and down-conversion mixers. Each SiGe circuit was designed, laid out, fabricated, and characterized before and after being irradiated, along with SiGe HBT *dc* and *ac* test structures needed for correlating changes in circuit performances back to device parameters.

The samples were irradiated with 63.3 MeV protons at the Crocker Nuclear Laboratory at the University of California at Davis. The dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. Ta scattering foils located several meters upstream of the target establish a beam spatial uniformity of 15% over a 2.0 cm radius circular area. Beam currents from about 20 nA to 100 nA allow testing with proton fluxes from 1.0×10^9 to 1.0×10^{12} proton/cm^{2}sec. The dosimetry system has been previously described [13][14], and is accurate to about 10%. At proton fluences of 1.0×10^{12} and 5.0×10^{13} p/cm^2, the measured equivalent gamma dose was approximately 135 and 6,759 krad (Si), respectively. The SiGe HBT *dc* test structures were irradiated with all terminals grounded, while the *ac* test structures and circuits were irradiated with all terminals floating. Previous studies have shown that this has minimal effect on the transistor-level radiation response [15]. All samples were irradiated to a proton fluence of 5.0×10^{13} p/cm^2, while the *ac* test structures were re-irradiated with another proton fluence of 5.0×10^{13} p/cm^2 resulting in a net fluence of 1.0×10^{14} p/cm^2. Since proton irradiation causes both ionization damage and displacement damage, the two cannot be easily separated without further neutron and gamma ray experiments (which are currently in progress).

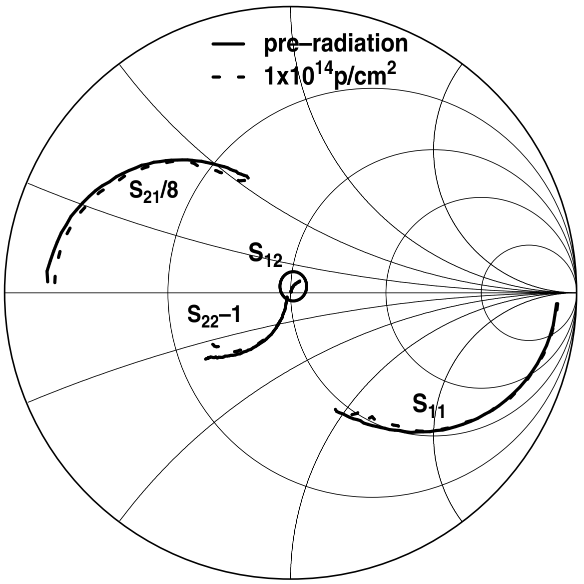

Fig. 3. Deembedded S-parameters at peak f_T.

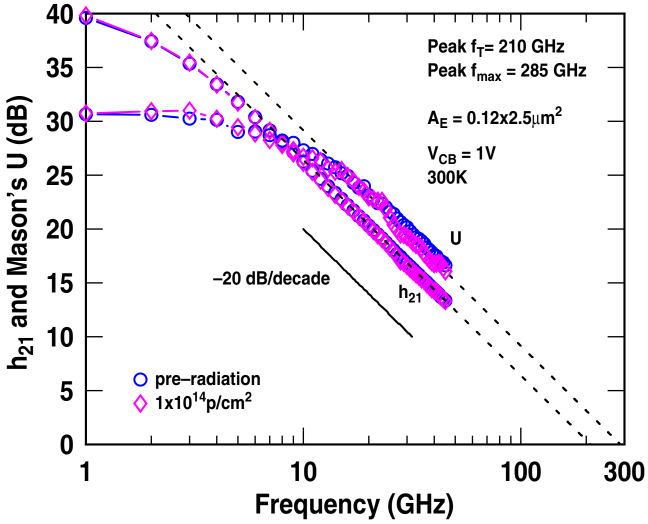

Fig. 4. Measured h_{21} and Mason's U versus frequency at peak f_T.

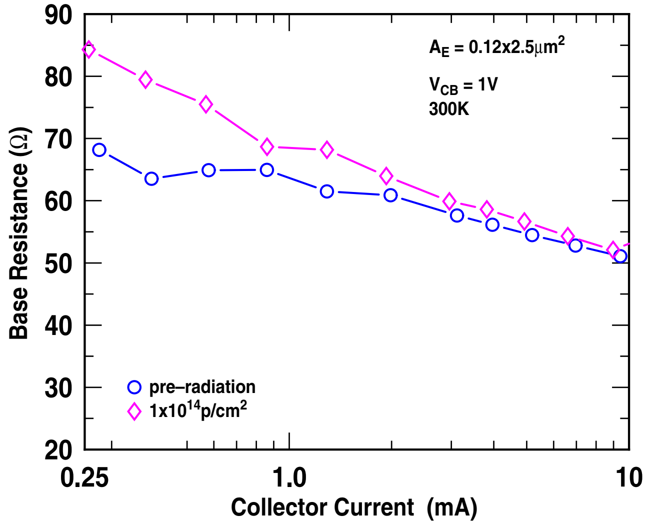

Fig. 5. Extracted base resistance (r_b) versus collector current.

IV. Transistor-level Response

Measurements of the SiGe HBT *dc* and *ac* test structures were made to quantify the transistor-level radiation response. Proton tolerance of a pre-production third-generation SiGe HBT technology has previously been reported in [16]. The SiGe HBTs used in this investigation represent an improved version of the one examined in [16], this time with an optimized ideal base current, reduced base resistance, and improved noise performance. The *dc* results obtained were in close agreement with the ones reported in [16] and, for brevity, are not repeated here.

The transistor scattering-parameters (S-parameters) were measured from 1 to 45 GHz at each bias point and subsequently deembedded using an "open-short" method. The current gain (h_{21}), Mason's unilateral gain (U), and base resistance (r_b) were then calculated from the deembedded S-parameters. The f_T and f_{max} were extrapolated from h_{21} and Mason's U with a -20 dB/decade slope line to 0 dB. Typical pre- and post-radiation deembedded S-parameters biased at peak f_T are shown in Figure 3, the associated h_{21} and Mason's U are shown in Figure 4, and the extracted r_b is shown in Figure 5. The extrapolated f_T and f_{max} up to 1.0×10^{14} p/cm^2 proton fluences are shown in Figure 6. Only slight variations were observed between the pre- and post-radiation results. The most apparent proton-induced device degradation lies in the increase of r_b in Figure 5, presumably caused by displacement effects in the neutral base region and the deactivation of boron dopants. Clearly, these third-generation SiGe HBTs are remarkably total-dose hard at the transistor level without any intentional hardening.

V. Low-Noise Amplifier

The LNA is a crucial building block in the SiGe monolithic mm-wave transceiver since it is the first gain stage in the receiver path used to amplify the weak incoming signals from the antenna. The noise figure (NF) of the LNA adds directly to that of the overall transceiver [17]. Thus, gain and NF are two key metrics, along with the input impedance match (S_{11}) and the output impedance match (S_{22}) [10].

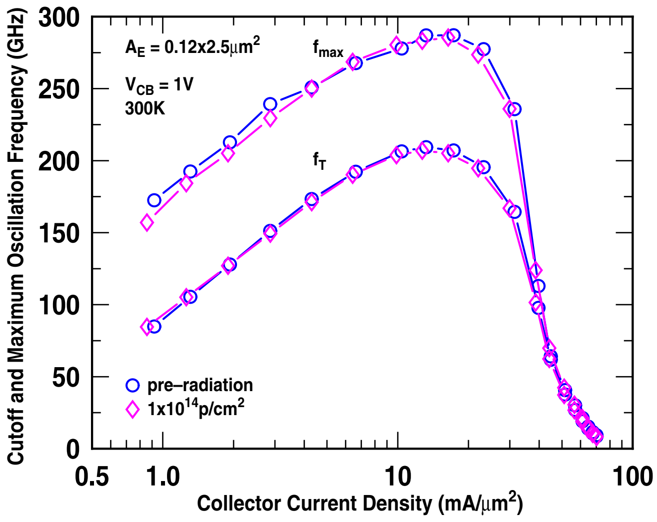

Fig. 6. Extrapolated f_T and f_{max} versus collector current density.

The 60 GHz SiGe LNA, whose schematic is shown in Figure 7, employs a two-stage architecture using microstrips [9]. The gain is adjustable by changing the second-stage bias current. The LNA die micrograph is shown in Figure 8, and the LNA occupies an area of 0.92×0.57 mm^2. The pre- and post-radiation LNA gain and NF are shown in Figure 9 and 10, respectively. The ripple in NF (Figure 10) is attributed to the measurement setup rather than to the LNA itself. The LNA gain decreased by 0.5 dB, NF increased by 0.4 dB, S_{11} remained unchanged, and S_{22} increased by 1.5 dB. Detailed results are summarized in Table II. The results are robust and repeatable.

The proton-induced changes in the SiGe LNA performance are minor, proving that it is robust from a total dose perspective for space applications. The increase in S_{22} may be attributed to the effects of proton irradiation on the microstrips and the SiGe HBTs, yet the LNA remains well-matched to 50 Ω. The degradation in gain may be attributed to the slight decrease in S_{21} (Figure 3) of the SiGe HBTs after irradiation. The increase in NF may be attributed to the increase in r_b (Figure 5) of the SiGe

HBTs, which adds directly to the NF of the LNA [10]. More detailed characterization of the proton-induced changes on the microstrips are needed to accurately quantify their effects on the LNA at mm-wave frequencies, and is in progress.

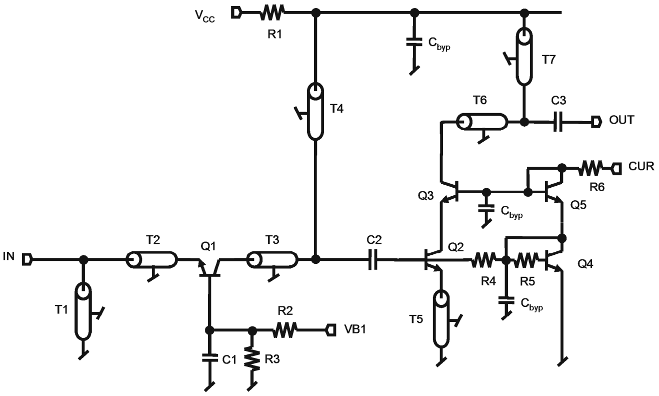

Fig. 7. Schematic of the SiGe LNA.

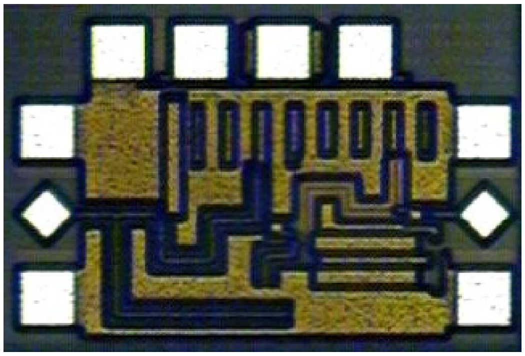

Fig. 8. Die micrograph of the SiGe LNA.

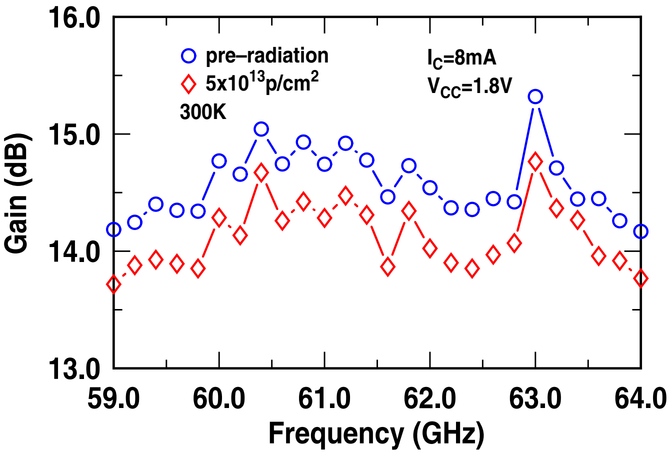

Fig. 9. Measured pre-and post-radiation gain of the SiGe LNA.

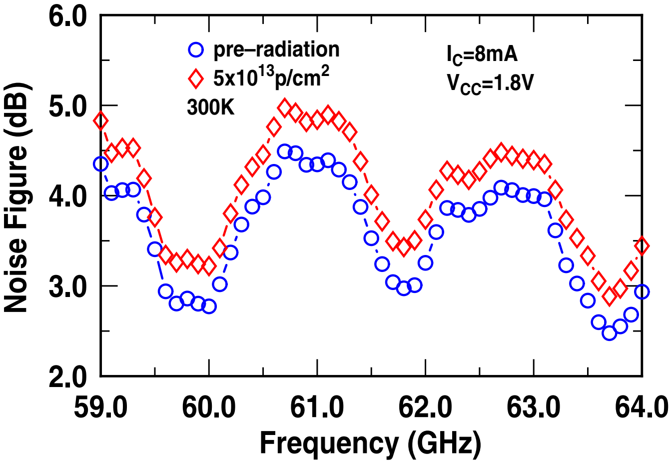

Fig. 10. Measured pre- and post-radiation noise figure of the SiGe LNA.

VI. VOLTAGE-CONTROLLED OSCILLATOR

The VCO is another key building block in the SiGe monolithic mm-wave transceiver. It is used to generate the local oscillator (LO) signals for the up- and down-conversion mixers needed to achieve frequency translation. Thus, the operating frequency of the VCO is a key performance parameter. The spectral purity of the VCO output is also key and is characterized by the phase noise. Phase noise can cause reciprocal mixing in the receiver and corrupt the wanted signal in the transmitter [17], both of which are detrimental to proper transceiver functionality.

The SiGe VCO, whose schematic is shown in Figure 11, employs a differential Colpitts architecture with microstrips and base-collector junction varactors [9]. The VCO die micrograph is shown in Figure 12, and the die occupies an area of 0.9 × 0.6 mm^2. The pre- and post-radiation VCO power spectra are shown in Figures 13 and 14, respectively. The VCO operating frequency shifted 0.3 GHz while the phase noise degraded 2 to 5 dB at 1 MHz offset. Detailed results are summarized in Table II.

The proton-induced changes in the SiGe VCO performance are minor, proving that it is robust from a total dose perspective for space applications. The shift in operating frequency may be attributed to the effects of proton irradiation on the microstrips and base-collector junction varactors that form the tank of the VCO, as well as on the SiGe HBTs. The degradation in phase noise may be attributed to an increase in SiGe HBT low-frequency noise ($1/f$) noise [18] that is up-converted into phase noise. Similar observations were made in [15], but in that case on a 5 GHz VCO using first-generation SiGe HBT technology. More detailed characterization of the proton-induced changes on the microstrips, base-collector junction varactors, and SiGe HBT $1/f$ noise are needed to accurately quantify their effects on the VCO at mm-wave frequencies, and are in progress.

VII. SUMMARY

The effects of 63.3 MeV proton irradiation on 60 GHz monolithic mm-wave transceiver building blocks implemented in third-generation SiGe HBT technology have been investigated for the first time. A SiGe HBT 60 GHz LNA and VCO were irradiated to proton fluences of 5.0 × 10^{13} p/cm^2. The degradation associated with these extreme proton fluences is found to be minor, suggesting that mm-wave SiGe transceiver building blocks should be robust to total ionizing dose for space applications. However, for complete radiation hardness qualification, total dose studies need to be complemented with thorough SEU sensitivity investigations. Since first generation SiGe HBT technology was prone to SEU sensitivity [19], the 200 GHz SiGe

TABLE II

SUMMARY OF THE SIGE TRANSCEIVER BUILDING BLOCK PARAMETERS

Block	Parameters	Pre-radiation	Post-radiation	Units
LNA	Frequency	61.5	61.5	GHz
	Gain	14.5	14.0	dB
	Mean NF	3.6	4.0	dB
	S_{11}	-6.0	-6.0	dB
	S_{22}	-18.0	-16.5	dB
	Vcc	1.8	1.8	V
	Ic	8	8	mA
VCO	Frequency	65.8 to 67.9	65.5 to 67.6	GHz
	P_{out}	-11	-11	dBm
	$L(1\text{ MHz})$	-98 to -102	-93 to -100	dBc/Hz
	Vcc	3	3	V
	Ic	8	8	mA

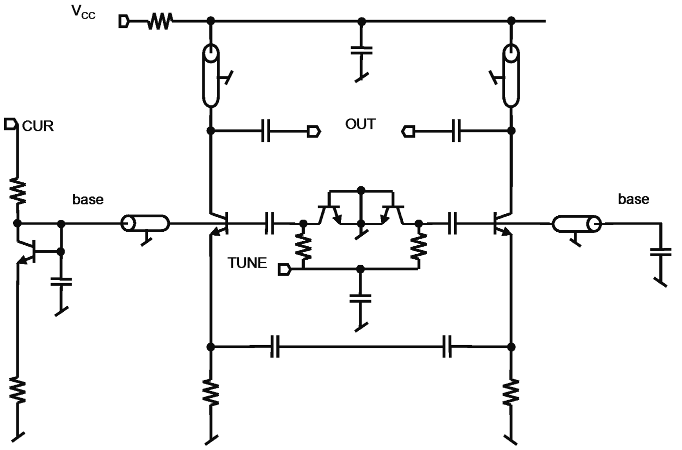

Fig. 11. Schematic of the SiGe VCO.

HBT technology might also be SEU sensitive and, hence, not be completely radiation hard.

VIII. ACKNOWLEDGEMENT

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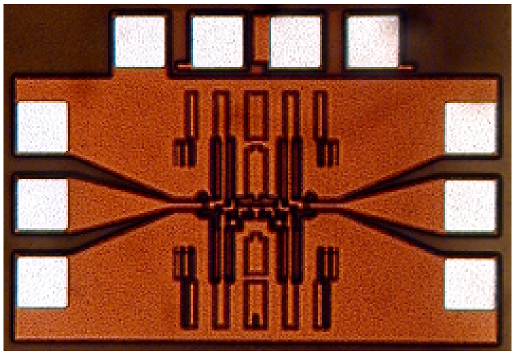

Fig. 12. Die micrograph of the SiGe VCO.

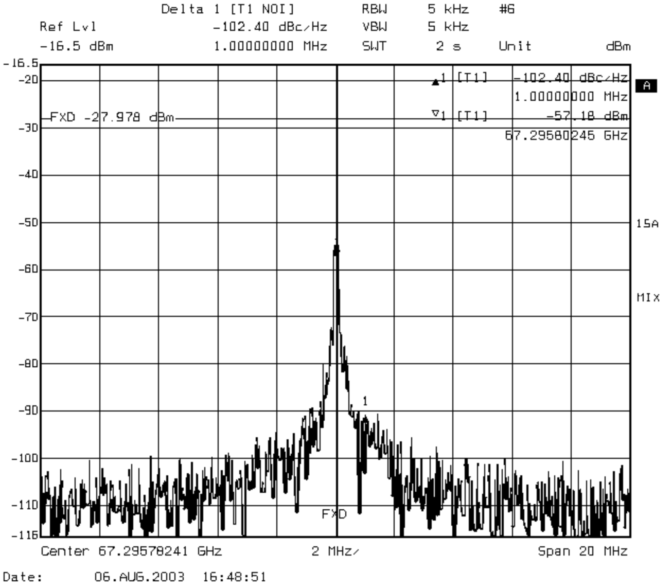

Fig. 13. The measured power spectrum of the pre-irradiated SiGe VCO.

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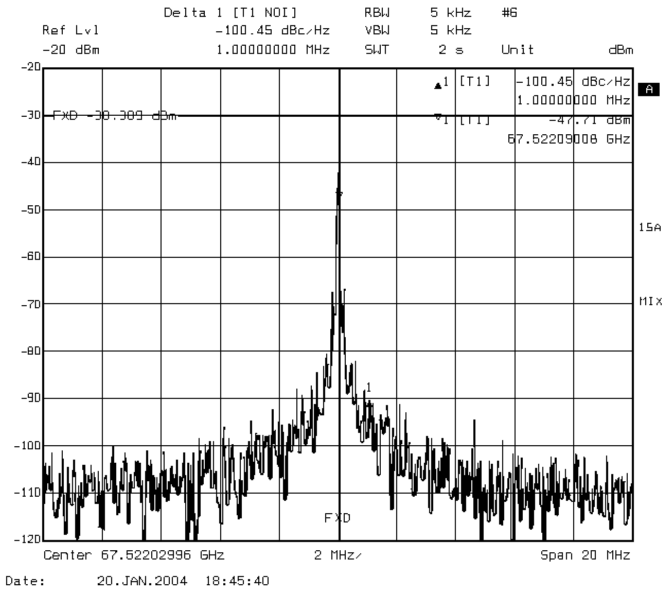

Fig. 14. The measured power spectrum of the post-irradiated SiGe VCO.

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