High-frequency SiGe MMICs – an Industrial Perspective (*Invited*)

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***Abstract* - After a brief discussion of the recent development of SiGe HBT technology, the state-of-the-art achievement of the technology in circuits implementation is reviewed from an applied perspective, focusing on microwave and mm-wave applications. In particular, the performance of SiGe HBT-based oscillator and receiver front-end ICs are presented and relevant industry issues are addressed.**

I. Development of SiGe Technology

SiGe technology is today one of the mainstream semiconductor technologies used in cellular communications. Even for higher frequency applications, well above 10 GHz, it is no longer a question whether or not the technology is feasible, but how it can be optimally deployed to either reduce cost, or improve performance, or enhance functionality. The rapid technology development has made SiGe being a viable alternative to III-V compound semiconductors for many microwave and millimeter-wave applications.

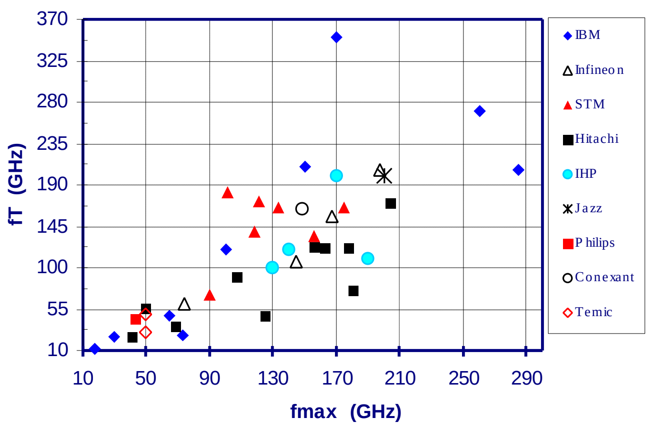

Fig. 1 collected fmax and the associated fT data for selected SiGe HBT vendors

Indeed, the development of SiGe heterojunction bipolar transistor (HBT) technology has progressed aggressively in recent years. In terms of the maximum cut-off frequency, fT, and the maximum oscillation frequency, fmax, SiGe HBTs have advanced from 100GHz of a few years ago to today's 300GHz and beyond in research laboratories (Fig. 1). For volume production, there are vendors offering today commercial access to technologies above 100 GHz.

As fT grows, the tolerance of the HBTs to electric stress diminishes as well. The open-base collector-emitter breakdown voltage, for instance, reduces from typically 2.5V for 100GHz technology to 1.5V or below for 300GHz generation. This low breakdown may pose a challenge when high dynamic range, or high power, or low phase-noise is a key requirement for circuits development.

II. High-frequency Circuits Implementation

A. *Low Phase-Noise Oscillator MMICs*

In oscillators operating at microwave frequencies, the 1/f-noise of the semiconductor devices in use is up-converted to close-to-carrier phase noise. Attributed to high interface quality of Si technology, SiGe HBTs have better low-frequency noise performance than any III-V transistors. The corner frequency, f_C, which is a characteristic measure of the 1/f noise, can be as low as 100Hz for SiGe HBTs, while the corresponding f_C for GaAs HBTs is typically order of magnitude higher, with GaAs HEMTs being even worse. This makes SiGe HBTs a favorable technology of choice for oscillator ICs.

We have designed SiGe MMICs of voltage-controlled oscillator (VCO) operating at 6 and 12 GHz in IBM's 5AM process [1] and at 21.5/43 GHz in STMicroelectronics' BiCMOS-7 process [2]. State-of-the-art phase-noise performance has been demonstrated. Normally, the breakdown voltage of the HBTs determines the maximum voltage swing in resonator tank and therefore limits phase-noise performance. Using the coupled-VCO idea, phase noise of -106dBc/Hz and -103dBc/Hz at 100KHz offset frequency are measured for the 6 and 12 GHz VCOs, respectively [1]. Fig. 2 shows the chip photograph of the 6 GHz VCO that consists of two identical, "single" VCOs coupled inductively together. Practically, it does not consume extra Si area than the "single" VCO.

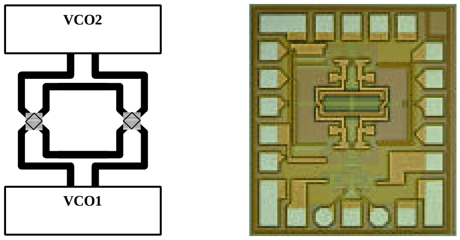

Fig. 2 block diagram and chip photograph of two inductively coupled VCOs (size: 1.1x1.2 mm^2)

We also designed a balanced Colpitts VCO that has duel-frequency outputs [2]. It demonstrated a measured phase noise of -93dBc/Hz and -87dBc/Hz at 100KHz offset for 21.5 GHz and 43 GHz oscillations, respectively (Fig. 3).

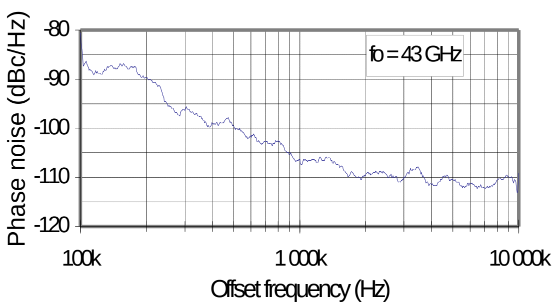

Fig. 3 measured phase-noise performance of the balanced Colpitts SiGe VCO operating at 43 GHz.

Following the work by Voinigescu *et al* [3], a number of high-frequency SiGe VCOs have been reported recently. Li and Rein designed integrated millimeter-wave VCOs with wide tuning range (26%) and low phase noise (better than -107dBc/Hz at 1MHz offset) [4-5]. Hackl and her co-workers constructed a 28GHz VCO with quadrature outputs and 15% tuning, but the phase noise is relatively high [6]. Recently, people from Infineon reported even a 98GHz VCO demonstrating -90dBc/Hz at 1MHz offset [7]. Fig. 4 shows the phase-noise data (normalized to 100KHz offset frequency) we collected for fully-integrated SiGe VCOs fabricated on standard Si wafers. Some results of III-V VCOs are also included for comparison.

When compared with Si bipolar or CMOS VCOs, primarily at low oscillation frequencies (Fig. 4), SiGe VCOs show marginally better phase-noise performance. At high frequencies, up to 50 GHz, they are at least comparable with III-V VCOs, if not generally better than. The demonstrated phase noise is sufficiently low to fulfill most industrial needs. Therefore, for signal generation purpose SiGe is technically qualified to replace III-V technologies.

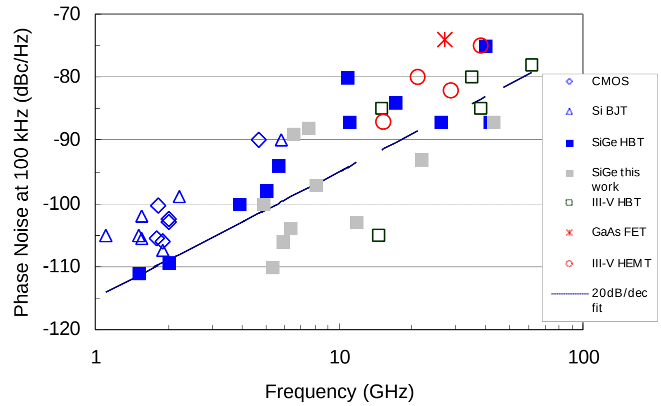

Fig. 4 collected phase -noise data of fully integrated SiGe VCOs, normalized to 100KHz using 20dB/dec slope when the original data are given for a different offset frequency

It is notable from Fig. 4 that the VCOs we developed are state-of-the-art in terms of absolute phase-noise. However, it should be pointed out that VCO tuning range and power consumption, two tradeoff parameters for better phase noise, are not considered in Fig. 4. When power consumption is included, for example, CMOS can be potentially better in terms of phase noise to power consumption ratio. It should be noted also that the SiGe VCOs presented in Fig. 4 were made in technologies with fmax of less or much less than 100GHz. Moving to more advanced technology does not necessarily guarantee an improvement in phase noise which, to a large degree, depends on the quality of passive elements as well. The lower breakdown in a faster process may also result in constraints on VCO design and thereby limit phase noise performance.

B. Receiver Front-End MMICs

1. Low-Noise Amplifiers (LNA)

Noise figure and linearity, which are inter-related, are two key parameters to consider as receiver front-end ICs are concerned. Except for being itself low noise, the LNA has to provide sufficient power gain to suppress the mixer's contribution to the overall receiver noise figure. This high gain translates into tough linearity requirement for the mixer.

Due to their low base resistance, high DC current gain and high fT, SiGe HBTs are superior in residual RF noise performance. They exhibit actually better noise figure than both Si bipolar and III-V HBTs. Therefore it is interesting to see whether SiGe HBT are advantageous for high-frequency LNA applications.

We have designed 23 GHz LNAs in Hitachi's and STMicroelectronics' BiCMOS technology [8-9]. Typically, 4dB noise figure and more than 20dB gain are obtained at this frequency. However, due to the high gain, the input-referred third-order intercept point (IIP3) is -6dBm, which limits the dynamic range of the receiver. One solution is to lower the gain and improve IIP3. The consequence is that the mixer noise figure has to be sufficiently low in order for the receiver noise figure to fulfill certain specification. Therefore, a mixer with high IIP3 and low noise figure is highly desirable.

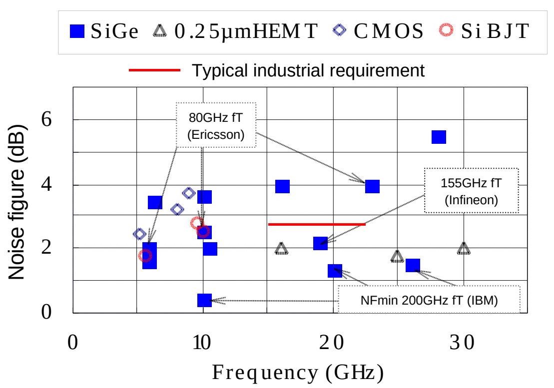

Fig. 5 collected noise figure data of SiGe LNAs.

Fig.5 shows the collected noise-figure data of SiGe LNAs. Some results from 0.25µm-GaAs HEMT LNAs are included for comparison. Clearly, SiGe HBTs are not competitive with III-V HEMTs in RF noise performance. Indicated in the figure is also a typical industrial requirement for noise figure. As can be noted, the LNAs developed in technologies featuring 80GHz fT do not meet the requirement. Recently, Infineon has developed an integrated 19GHz SiGe LNA that demonstrated 2.2dB noise figure and 26dB gain using their 155GHz-process [10] (fig 5). IBM, in its 200GHz technology, obtained minimum noise figure of 0.4, 1,33 and 1.5dB at 10, 20 and 26 GHz, respectively [11] (Fig. 5). These results get close to those of 0.25µm-GaAs HEMTs. Therefore, moving to more advanced SiGe technology featuring larger-than-100GHz fT will certainly facilitate LNA application of the technology at high frequencies.

2. Active Mixers

As discussed earlier, a desirable mixer would be low noise and highly linear. Conversion loss is normally not a concern for bipolar mixers that are almost exclusively active.

A double-balanced Gilbert topology is applied in our mixer design [12]. In addition to positive conversion gain, such a mixer may offer moderate noise figure and requires no complicated filtering to achieve adequate port-to-port isolation. Its linearity, however, is relatively poor as compared with passive mixers. In order to improve the linearity, a linearizer consisting simply of a shunt diode is placed prior to the RF input (Fig. 6). This linearization technique has been used for power amplifiers and it is demonstrated here that the same method may be applied for mixers as well.

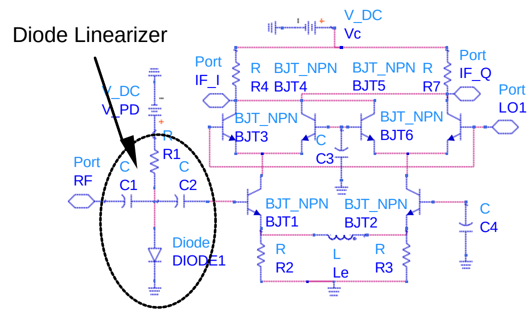

Fig. 6 circuit schematic: Gilbert mixer with a diode linearizer

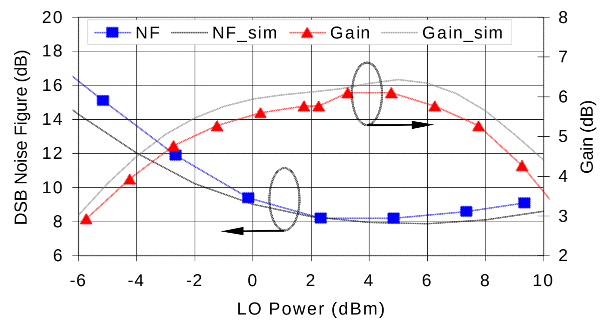

Fig.7 DSB noise figure and conversion gain vs. LO power for the mixer without linearizer: f_{RF}=23GHz, f_{IF}=1GHz

The double-side-band (DSB) noise figure and gain vs LO power are shown in Fig. 7 for the Gilbert mixer without linearizer that down-converts a 23GHz RF signal to a 1GHz IF. Measurement and simulation agree excellently. The measured noise figure of 8.2dB around 3dBm LO power is considered to be low for mixers of this kind.

When the linearizer is applied, the IIP3 can be improved by as much as 7dB, as seen from Fig. 8 where measured IIP3 data are compared for mixers with and without the linearizer. The cost for this improvement is 4dB lower gain and 2dB higher noise figure. The technique is therefore recommended when linearity is more concerned than gain, which is normally the case when an active mixer is used.

IIP3 may be improved also by using large DC biasing. When this approach is adopted, the low breakdown voltage of advanced SiGe HBTs is again in question. Industrial engineering will benefit tremendously if future generation of SiGe technology remains to offer devices of both high and low breakdown within a same process platform.

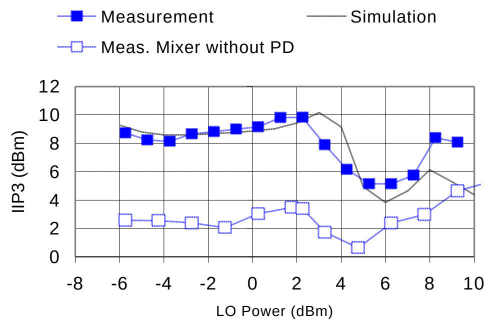

Fig. 8 measured IIP3 vs LO power for mixers with (solid squares) and without (open squares) the linearizer.

3. Integrated Low-Noise Converter (LNC)

Encouraged by the performance achievement of SiGe LNAs and mixers, a natural step forward is to design a monolithic receiver front-end. In fact, Sönmez et al reported an integrated SiGe 24GHz front-end [13] earlier, though the performance is regarded as insufficient due partially to the less-advanced technology used then.

We made a first attempt of an integrated LNC. The LNA and the mixer, each optimized to 50Ω source and load impedance, were simply connected together to form a single chip. The measured overall conversion gain was 28dB, almost identical to the sum of LNA gain and mixer conversion gain. However, the DSB noise figure was 7dB that is almost 3dB higher than what is expected from simulation (the simulated noise figure is consistent with prediction using the Frii's formula.) While further investigation is needed to identify the exact source of the high noise figure, there is a potentially high possibility that it is caused by coupling between LNA and mixer through Si substrate, a crucial aspect when working at high frequencies on Si.

III. Conclusions

While maintaining the volume-manufacturing infrastructure of conventional Si, SiGe technology offers today high-frequency capability competitive with III-V semiconductors. It is superior to use SiGe HBTs in oscillator design and VCOs with sufficiently low phase-noise have been demonstrated up to 50 GHz. For high-frequency LNA applications SiGe technologies of less-than-100GHz fT are found not enough to meet industrial requirements. With more advance generation (e.g., >120GHz), however, the noise performance of SiGe HBTs gets comparable with that of 0.25µm GaAs HEMTs and LNAs with noise figure below applied specifications have been reported. These performance capabilities, together with the economic and integration advantages, will motivate the replacement of GaAs by SiGe in many high-frequency products.

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