SILICON-MONOLITHIC INTEGRATED MILLIMETERWAVE CIRCUITS FOR VEHICULAR TECHNOLOGY

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Abstract

Within the next decade intelligent millimeterwave radar systems for vehicular sensor applications in the frequency band from 77 GHz to 81 GHz will be developed in Germany. State of the art in passive and active components of monolithic integrated silicon millimeterwave systems is discussed and the data of already realized components are presented.

Introduction

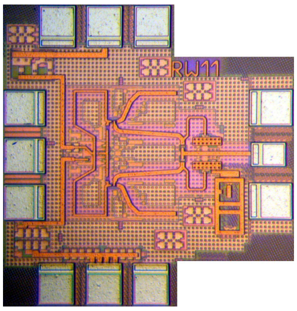
Silicon as a substrate for millimeter-wave monolithically integrated circuits has been suggested in 1981 by the RCA group of A. Rosen et al [1]. Since 1986 in the field of **si**licon **m**onolithic **m**illimeter**w**ave **i**ntegrated **c**ircuits (SIMMWICs) there have been research activities in the area of SIMMWICs [2–8]. Up to now SIMMWICs for frequencies up to above 100 GHz already have been fabricated, and the suitability of silicon as the base material for monolithic integrated millimeterwave circuits has been successfully demonstrated. Modern silicon technology allows to realize complete front-ends including antenna arrays in monolithic integrated silicon technology [4, 8]. The SiGe heterojunction bipolar transistor enables the break-through of Si based MMIC (Monolithic Millimeter-Wave Integrated Circuit) technology [9]. Amplifiers and tunable oscillators with maximum operation frequencies beyond 80 GHz are feasible. Infineon's SiGe bipolar production technology B7HF200 is capable for high volume production [10].
SiGe hetero bipolar transistor technology with transistor transit frequencies beyond 200 GHz allows the realization of oscillator, mixer, modulator and demodulator circuits for 80 GHz operating frequencies. The short wavelength allows to integrate complete antenna arrays on silicon substrate together with antenna feed, mixer and oscillator circuits. Complete front-end integration reduces costs and minimizes fabrication tolerances. MMICs can be fabricated with high precision concerning geometric dimensions and material parameters. This minimizes phase errors and allows precise beam-forming in antenna arrays. Beam-forming is achieved either by phase control in the antenna feeding networks or via modulation.
Monolithic integration of solid-state devices provides the possibility of low-cost production, improved reliability, small size and light weight, and easy assembly. In the frequency region above 60 GHz, SIMMWICs with dimensions of only a few millimeters may also include planar antenna structures. The integration of the antenna structures allows the direct coupling of SIMMWICs to the radiation field.
Monolithic integrated millimeterwave circuits based on silicon and SiGe will give new options for millimeterwave sensor and communication applications. Compared with microwave based systems millimeterwave based systems offer the following advantages:

- Availability of broader frequency bands.
- Higher gain and smaller dimensions of antennas.
- Lower weight and smaller size of the components.
- Higher resolution for sensor applications.
- Atmospheric attenuation may prevent interference between cells.

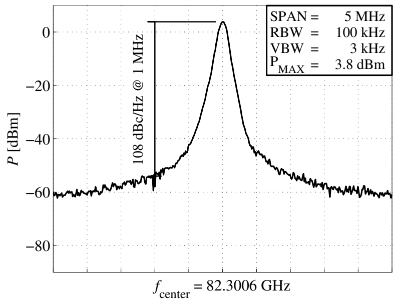
A broad application of millimeterwaves in sensors and communications has been hampered up to now due to the high costs of millimeterwave components. This situation may change in the future due to the availability of low-cost monolithic integrated components based on a silicon and SiGe technology.

Monolithic Integrated Millimeterwave Circuits

Numerous examples of Si/SiGe based monolithically integrated RF chips of high performance have been presented in literature.

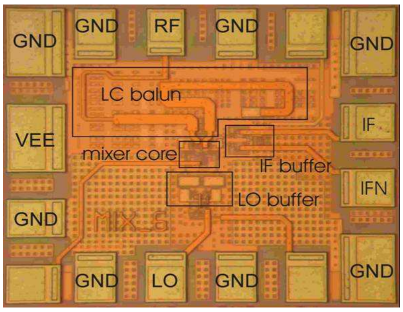


(a) Chip photograph

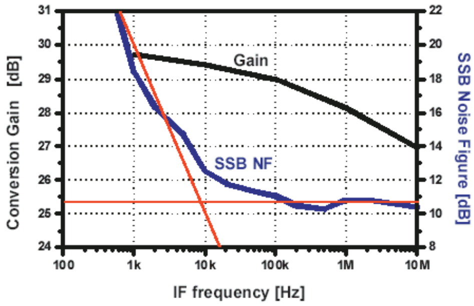


(b) Measurement

Figure 1: 82 GHz push-push VCO



(a) Chip photograph



(b) Conversion Gain and SSB Noise Figure

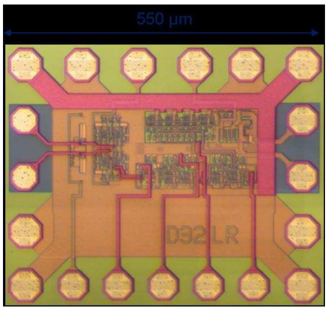
Figure 2: 77 GHz Active mixer.

A 100 GHz broadband amplifier in 200 Ghz SiGe Bipolar Technology with 16 dB gain and 62 GHz has been realized [11]. Figure amplifier chip has dimensions of $550 \times 550 \mu\text{m}^2$

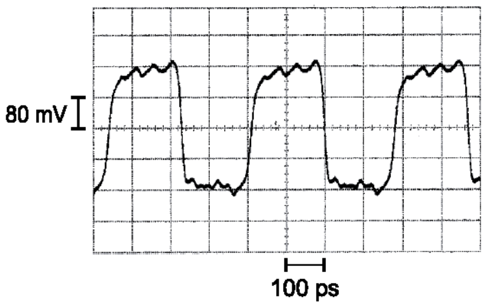
SiGe bipolar technologies are well suited for voltage-controlled oscillators (VCOs) in 77-GHz automotive radar systems [12]. Monolithic integrated HBT oscillators with oscillation frequencies up to 74 GHz have been reported [13–15]. A 47 GHz MMIC SiGe-HBT oscillator with an output power of 13.1 dBm, an efficiency of 13.6 %, and a phase-noise of -99.31 dBc/Hz at 100 kHz off-carrier has already been realized [16]. Applying the push-push principle a monolithic integrated 150 GHz SiGe HBT VCO with -5 dBm output power at 150 GHz and 30 GHz tuning range [17] already has been realized. A monolithic integrated 82 GHz push-push oscillator has been realized in SiGe:C bipolar technology [18, 19]. The oscillator output frequency can be tuned from 80.6GHz to 82.4 GHz. In this frequency range the measured output power is 3.5 ± 0.4 dBm while the measured single sideband phase noise is less than 105 dBc/Hz at 1MHz offset frequency. The transistors exhibit a transit frequency $f_T = 200$ GHz and a maximum frequency of oscillation $f_{max} = 275$ GHz. The chip with dimensions 700 μm$\times$700 μm is depicted in figure Figure 1. For a varactor voltage VVC = 2.05V the output power reaches its maximum of 3.9 dBm. The measured single side band phase noise level goes to its minimum of -108 dBc/Hz at an offset frequency of 1MHz at a varactor voltage VVC = 1.8 V. Figure 1 shows the measured spectrum at the first harmonic frequency of the oscillator signal. A fully integrated SiGe VCOs with output buffer for 77-GHz automotive Radar systems and applications around 100 GHz has been realized [12]. At a center frequency of around 77 GHz, a tuning range of 6.7 GHz and a phase noise of -97 dBc/Hz at 1-MHz offset frequency were achieved. The total signal power delivered by both buffer outputs together is 18.5 dBm.

An active down-conversion mixer for automotive radar applications at 76 GHz to 81 GHz was realized in a 200 GHz f_T SiGe bipolar technology [20]. A conversion gain of more than 24 dB and a single-sideband noise figure of less than 14 dB is achieved. The 1 dB output compression point is -4 dBm. The power consumption is 300 mW at -5 V supply voltage. Figure 2 shows the chip photograph and the frequency dependence of gain and SSB noise figure.

Static and dynamic frequency dividers were realized in a 200 GHz f_T SiGe bipolar technology [21]. The static divider has a divide ratio of 32 and operates up to 86.2 GHz. The dynamic divider is based on regenerative frequency division and has a divide ratio of two. It operates up to 110 GHz (limited by the measurement equipment). Figure 3 shows the chip photograph and the single ended output signal at 86.2 Ghz input.



(a) Chip photograph



(b) Single ended output signal at 86.2 Ghz input

Figure 3: 110 GHz dynamic frequency divider.

Passive Circuit Structures on Silicon

The linear passive parts of SIMMWICs may be realized in planar circuit technology. The fundamental transmission line structures used in SIMMWIC design are microstrip lines, slot lines, coplanar lines, coplanar strip lines, and microshield lines. Based on these fundamental geometric structures the planar circuit elements are designed. These planar circuit elements include transmission line discontinuities, planar resonators and antennas as the basic structures.
With planar circuit structures resonators, filter circuits, power dividers, matching networks and planar antennas may be realized [5]. It is possible to combine different functions so that circuits with extremely small dimensions can be realized and furthermore losses in a connection line between oscillator and antenna are avoided.
Further reduction of microwave monolithic integrated circuit (MMIC) dimensions will require multilayered wiring and transmission line structures with cross-sectional dimensions of the conductors in the order of micrometers. In order to achieve further reduction in conductor losses, copper is also considered for internal wiring [22]. Distributed passive circuits in MMICs require electromagnetic full-wave modeling [23].

Planar Antennas

In the millimeter wave region with small antenna dimensions a considerable antenna gain may be achieved. This allows to include planar antenna structures into SIMMWICs [8]. Using integrated antennas as the radiating structures, feed lines and associated components, such as oscillators, detectors and mixers may be combined. Planar antennas with 36 elements and with 96 elements have been designed and fabricated [3,24]. The design of planar antenna arrays in the millimeterwave region involves new problems, since substrate surface waves may increase mutual coupling between the antenna elements, and losses in the feed lines limit the array size.
The patch antenna is the most commonly used planar millimeter wave antenna and the basic antenna element for antenna arrays. The application of these antennas, however, is limited by their narrow bandwidth. At millimeterwave frequencies they suffer from excitation of surface wave modes and from losses in the feed lines. Excitation of surface wave modes results in poor radiation efficiency and in mutual coupling of antenna elements in antenna arrays. Compared with patch antennas slot antennas exhibit a higher bandwidth. The slot length equals one line wavelength. Coplanar active devices can be placed within the radiating aperture and the slot simultaneously acts as a resonator [25, 26].
The first active integrated K-band antenna on high resistivity silicon substrate employing a Si/SiGe HBT was presented in [27, 28]. Microstrip structures represent the resonating and radiating circuits. The HBT was mounted in flip-chip technique. An output power of 20 dBm at 24 GHz has been achieved.

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