A Scalable 8-Channel Bidirectional V-Band Beamformer in 130 nm SiGe:C BiCMOS Technology

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***Abstract*—This paper presents an 8-channel bidirectional 60 GHz beamformer in a SiGe:C 130 nm BiCMOS technology, with $f_T / f_{max} = 250 / 340$ GHz. The beamformer consists of RF switches, LNAs, PAs, vector modulators, passive dividers / combiners and an integrated SPI controller. On wafer measurements results show that the beamformer has an OP1dB of 0 dBm in Tx mode and an IP1dB of -26 dBm in Rx mode, consuming only 550 mW in both operation modes and occupying a silicon area of 27 mm^2.**

***Index Terms*— V-band, beamforming, phased-array.**

I. Introduction

The recent years have witnessed an increasing interest for the development of high-speed low-cost communication systems at V-band. A lot of research has been focused in particular on phased-array systems, either considering receiver (Rx) and transmitter (Tx) on separated chips [1]–[3] or within a single one [4]. Such phased-arrays are able to provide high data-rate beam steering. In [5], 16-QAM modulated data has been transmitted at a speed of 3.85 Gbps over a distance of 4 m with a scanning angle of ±45°. All the cited solutions include an up / down converter together with the beamformer itself. This means that they translate the signals in frequency from radio frequency (RF) to baseband (BB) in Rx mode, and from BB to RF in Tx mode, within the same chip which performs beamforming. In such a way, the number of channels is defined on chip and cannot be changed.

A more flexible solution considers the use of bidirectional beamformers with V-band input and output, without any internal frequency conversion. In this context finds place the work introduced in the present paper, where an 8-channel bidirectional beamformer containing RF switches, low noise amplifiers (LNAs), power amplifiers (PAs), vector modulators, passive dividers / combiners and an integrated SPI controller, is designed and characterized on wafer. Such a beamformer can be used in complex systems, where multiple beamforming chips can be connected to a unique up / down converter. The dividers / combiners for splitting / combining the signals in the path between up / down converter and beamformers are intended to be designed on a low cost printed circuit board (PCB). In this way, the number of beamformers can be chosen and many different systems can be built in a modular way, designing from time to time only an ad-hoc PCB. Fig. 1 brings as examples two different architectures which exploit the modularity given by a bidirectional beamformer. Such modularity makes a system of this kind exploitable for different applications, since its main characteristics (power consumption, overall size, total transmitted power etc.) can be defined based on the targeted use scaling the number of used beamformers.

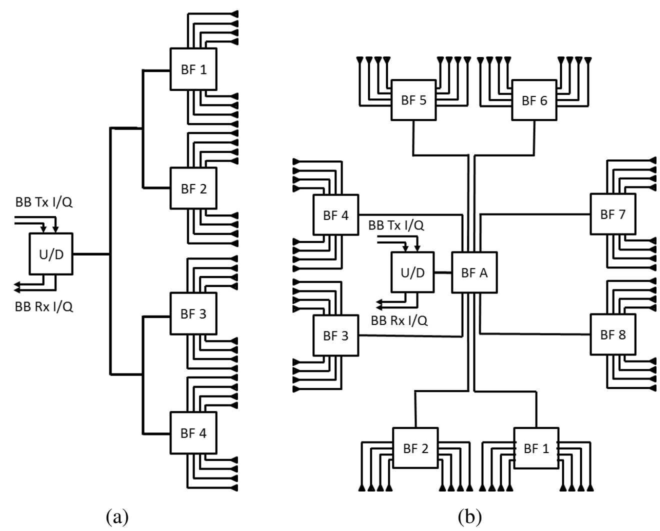

Fig. 1. Examples of modular beamforming systems: tree (a) and star (b).

This paper is organized as follows. Section II describes the overall architecture and, afterward, the details of all the circuit blocks employed within the beamformer. In Section III the results of small-signal, large-signal and speed measurements are reported. Section IV concludes the paper giving a comparison with the state of the art V-band beamforming systems.

II. Circuit design

The block diagram of the designed beamformer is shown in Fig. 2. It consists of three different sub-sections: trans-

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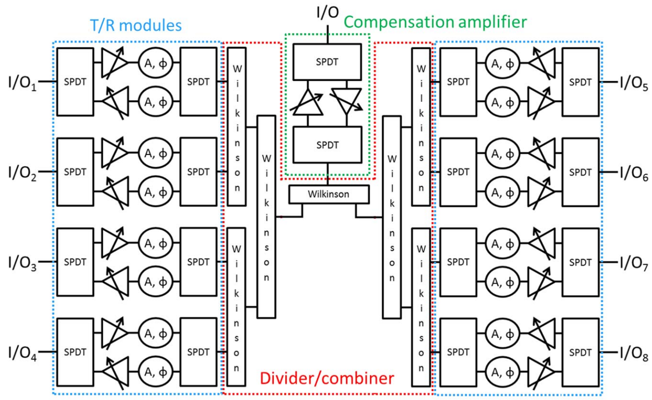


Fig. 2. Beamforming chip block diagram.

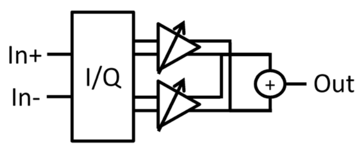


Fig. 3. Vector modulator architecture.

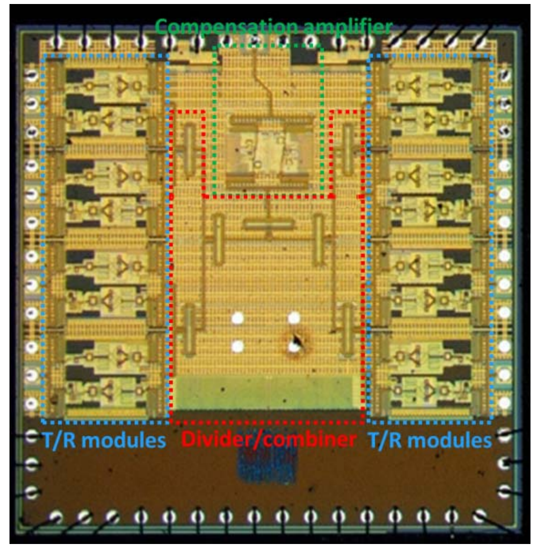
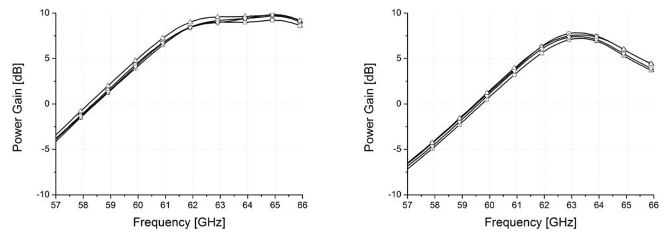


Fig. 4. Beamforming chip photomicrograph.



(a) (b)

Fig. 5. Small-signal power gain along 4 of the 8 channels in both Rx (a) and Tx (b) mode.

mit / receive (T / R) modules, divider / combiner tree and compensation amplifier.

A. T / R modules

The T / R modules consist of different building blocks. Two single pole double throw (SPDT) switches decide whether the module works in Tx or in Rx mode. In Rx mode, a variable gain LNA amplifies in a low noise fashion the received signal, which is then adjusted in phase and amplitude by a vector modulator. In Tx mode, the signal is at first phase shifted and tuned in amplitude by a vector modulator and afterward transmitted with maximum power through a variable gain PA. Both LNA and PA are single stage cascode amplifiers. The vector modulator block shifts in phase and adjusts the amplitude of the signal at its input exploiting two variable gain amplifiers (VGAs) connected in quadrature, whose outputs are summed in a vectorial way, as visible in Fig. 3.

B. Divider / combiner tree

The function of spreading the single V-band signal into the eight channels in the Tx mode and combine the 8 received signals into a single one in the Rx mode is enabled by a three levels divider / combiner tree. Each divider / combiner is a passive coplanar grounded waveguide (CPW)-based Wilkinson structure with less than 1 dB losses.

C. Compensation amplifier

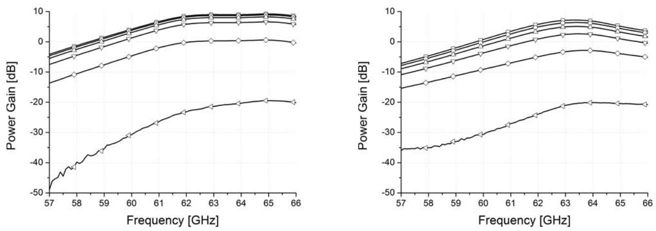
The losses introduced by the passive divider / combiner tree are compensated by a bidirectional variable gain amplifier here called compensation amplifier. It consists of a two stages cascode amplifier, where small resistors between collector and supply improve the stage-to-stage isolation and therefore the overall stability. SPDT switches as the ones used within the T / R modules are here reused to make the compensation amplifier bidirectional.

III. Measurement results

The beamforming chip has been manufactured and measured, and its chip photomicrograph is here depicted in Fig. 4. In order to be tested, its DC pads have been wire-bonded to a test board, while its RF pads have been contacted using on-wafer probes. The chip has then been characterized looking at its small and large signal behavior. The gains of all the amplifiers have been controlled through the SPI interface. The speed of the switches has also been tested through time domain measurements.

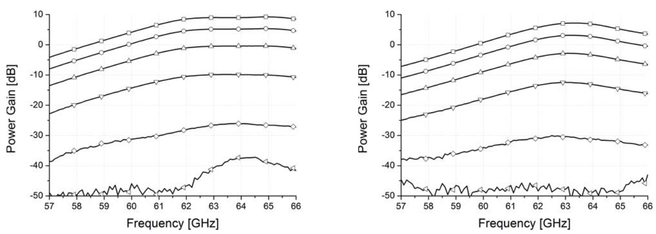
A. Small-signal measurements

The measured small-signal power gain in Rx and Tx mode is shown in Fig. 5 for four of the eight channels. The same gain is shown in Fig. 6 and Fig. 7, where LNA and PA gain and compensation amplifier gain have been swept respectively. A peak gain of 9.8 dB in Rx mode and 7.8 dB in Tx mode has been reached in all the channels. The gain of the chain can be controlled within more than 40 dB. Fig. 8 shows the polar plots obtained varying the vector modulator state in both Rx and Tx mode. From such polar plots it can be noticed how a complete 2π phase rotation has been obtained.



(a) (b)

Fig. 6. Small-signal power gain sweeping LNA gain in Rx mode (a) and PA gain in Tx mode (b).



(a) (b)

Fig. 7. Small-signal power gain varying the compensation amplifier gain in both Rx (a) and Tx (b) mode.

B. Large-signal measurements

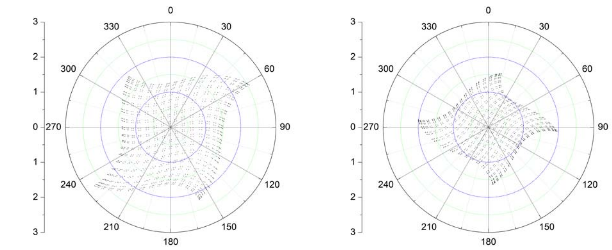
The input power has been swept in both Rx and Tx mode in order to obtain the 1 dB compression point (P1dB) of the system. These results are reported in Fig. 9. In Rx mode an input P1dB (IP1dB) of -26 dBm has been achieved, while the output P1dB (OP1dB) measured in Tx mode is 0 dBm.

C. Speed measurements

Both operation mode and vector modulator state can be controlled directly from dedicated control signals without passing through the SPI. Both output and control signal have been monitored using an oscilloscope, in such a way that the delay between them gives an upper limit for the transition time. By performing this kind of measurements, it has been seen how in order to switch fully from Rx to Tx mode and vice versa the system needs less than 40 ns, while the transition between two different vector modulator states requires less than 15 ns. Such a speed makes the chip suitable for time-division multiplexing in multi-user scenarios.

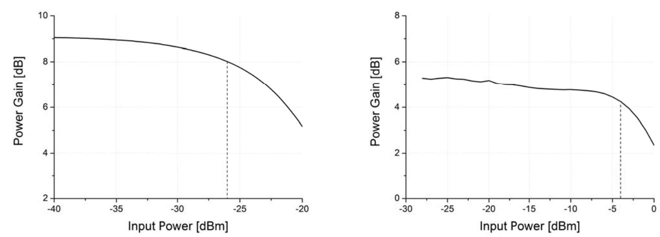
IV. Conclusion

In this paper an 8-channel bidirectional 60 GHz beamformer in a SiGe:C 130 nm BiCMOS technology has been presented. The measurement results are summarized and compared with the state of the art in Table I. Occupying an area of 27 mm^2 and consuming a DC power of 550 mW in both operation modes, the beamformer performance is comparable to the state of the art. The fine controllability of both amplitude and phase of the treated signal gives to the circuit a high configurability degree and allows to performs accurate calibrations. The full bidirectionality of the beamformer makes it suitable for different flexible modular solutions within massive arrays with large number of antennas.



(a) (b)

Fig. 8. Polar plot of the power gain in both Rx (a) and Tx (b) mode at a frequency of 62 GHz.



(a) (b)

Fig. 9. Power gain versus input power in both Rx (a) and Tx (b) mode, measured at 63 GHz and 62 GHz respectively.

TABLE I
Comparison of V-band beamforming systems.

	[4]	[1]	[2], [3]	This Work
Technology	90 nm CMOS	65 nm CMOS	120 nm SiGe	130 nm SiGe
Number of channels	32	32 Tx / 4 Rx	16	8
Rx IP1dB [dBm]	-28	—	-37	-26
Tx OP1dB [dBm]	-3.5	9	9.3	0
Rx P_{DC} [W]	0.85	0.71	1.8	0.55
Tx P_{DC} [W]	1.2	1.82	3.8	0.55
Area [mm^2]	29	72.7 Source 77.2 Sink	43.9 Tx 37.7 Rx	27
Integration level	U / D Conv. Synthesizer Beam former	U / D Conv. Synthesizer Beam former	U / D Conv. Synthesizer Beam former	Beam former
Bidirectionality	Yes	No	No	Yes

V. Acknowledgments

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