We demonstrate for the first time a full-fledged millimetre-wave graphene-based receiver frontend. The circuit is a six-port receiver frontend at 90 GHz employing graphene power detectors. Exploiting the strong nonlinearity and the high responsivity of the state-of-the-art graphene field effect transistors (GFETs), graphene power detectors are demonstrated beyond the maximum oscillation frequency $f_{\text{max}}$ of the graphene transistor. The proposed circuit is fabricated on thinned SiC substrate and its functionality is proofed by demodulation of 10 Mbps On-Off keying (OOK) digitally-modulated signal.

I. INTRODUCTION

Graphene attracted great interest since 2004 after two physicists reported their observation of electric field effect in two-dimensional single carbon atom sheets [1]. Since then, the main concern is to develop electron devices, in particular transistors, to exploit the excellent electrical properties of graphene such as the high carrier mobility and saturation velocity. However, few circuits have been reported to exploit the capabilities of graphene devices to demonstrate graphene-based circuits for high frequency applications. This is mainly due to: the limited maximum oscillation frequency $f_{\text{max}}$ reported for graphene field effect transistors (GFETs) [Add reference]. In addition, the gapless band-structure of large-area graphene sheets results in poor current saturation which in turn limits the usage of GFET as other normal field effect transistor in conventional circuits. Hence, most of the reported GFET-based circuits; such as mixers [1], frequency multipliers [1], and power detectors [1], exploit the nonlinearity of the GFET rather than its transconductance. This approach slower the pace of developing graphene-based systems such as communication receivers. A graphene radio frequency (RF) receiver has been reported [1] at 4.3 GHz employing GFET-based three-stage amplifier by using the last stage as a mixer [1]. In this receiver, the mixer conversion loss is partially compensated by the preceding two-stage amplifier and, hence, this receiver architecture is limited to the $f_{\text{max}}$ of the implemented GFETs. Otherwise, the circuit will provide high loss, which in addition to the mixer conversion loss degrades the receiver sensitivity. In this letter we adapt the receiver architecture to the available GFET devices to demonstrate for the first time, millimetre-wave graphene receiver frontend. The concept of six-port wave-correlator is employed together with GFET-based graphene power detectors which can operate beyond its $f_{\text{max}}$ preserving excellent nonlinearity and responsivity, to demonstrate a full-fledged fully integrated receiver frontends at 90 GHz SiC substrate. The circuit is implemented on custom-developed MMIC processes which enable high performance passive components. The circuit functionality is proofed by demodulation of 10 Mbps On-Off keying digitally-modulated signal at 90 GHz.

II. SIX-PORT RECEIVER CONCEPT

Six-port receiver architecture has drawn a lot of attention for wideband, low-power, and low-cost applications. The concept of operation is based on the linear addition of a complex-modulated input signal and a reference signal. The added signals are squared by a nonlinear element, such as power detector, and low-pass filtered to the baseband bandwidth. Introducing relative phase shifts of 0, 90, -90, and 180 to the input paths of the six-port wave-correlator, allows creating linear independent power measurements at the receiver outputs and, hence, the original quadrature components of the modulating signal; I and Q, are represented with four power detectors readings. Accordingly, a full-fledged direct conversion receiver can be obtained by utilising only one linear passive six-port junction and four power detectors. The proposed six-port receiver architecture is illustrated in Fig. 1. It consists of three 90 hybrid couplers, one Wilkinson power combiner and four graphene power detectors. Compared to other receiver architectures, the six-port receiver is of low complexity and requires only a reference local oscillator signal as an active high frequency component besides a low-noise amplifier if the required dynamic range of the receiver signal is beyond 40 dB.

Fig. 1. Architecture of RTWO with transmission line and lumped components causing 45° phase shift in each branch
III. W-band Six-port Receiver Design

A. GFET-based power detectors

Graphene transistors can be used as power detectors by exploiting the strong nonlinearity of the graphene channel resistance. Hence, the input-output square law behaviour is obtained which enables ultrawideband detection with more than 40 dB dynamic range and a detection responsivity of 33 V/W at 110 GHz [6], [7]. It has been shown, that a power detector using single GFET device can demodulate up to 4 Gb/s On-Off keying signal at 96 GHz [8]. Accordingly, the circuit configuration in Fig. 2(a) is designed as power detector employing single GFET device fabricated by hydrogen intercalated bilayer epitaxial-grown graphene on 100 m SiC substrate. The input signal is fed to the GFET gate which is biased through an RF choke, while the dc output is extracted at the drain using a second RF choke. The measured detector responsivity is higher than 4 V/W up to 70 GHz for 0 V gate bias as shown in Fig. 2(b). Fig. 2(c) illustrates the small-signal S-parameter measurements of the GFET-based power detectors which are used to design the input and output matching networks in the receiver circuit reported in this paper.

B. six-port junction design

Hybrid implementation is commonly used for the six-port junction to realise both couplers and power combiners because it provides low losses and wideband operation. A hybrid passive six-port junction was designed using three identical Lange couplers and one Wilkinson power combiner. Figure 4 shows a stand-alone test cell for a wideband Lange coupler which provides quadrature outputs from 70 to 110 GHz. The phase measurements match well with the simulated values in the entire frequency band with a 3 phase discrepancy at 90 GHz. While the amplitude measurements have different trends compared to the simulation but with acceptable discrepancy of about 1 dB at 90 GHz. Good matching is also noticed at all ports looking at the measured return losses.

IV. Measurement Results

The chip micrograph of the six-port receiver is shown in Fig. 5 which illustrates different building blocks of the receiver as well as the GFET power detectors. Reactive matching networks are used to maximize the power transferred to the gate of each power detector. While at the baseband outputs of the power detectors, microstrip lowpass filters are used to suppress any high frequency signal. One dc pad is used to bias the gate of all GFET power detectors, concurrently. The measurements of the W-band receiver are shown in Fig. 5(b) and indicate successful demodulation of a 10 MHz On-Off Keying (OOK) modulated input signal over the frequency range from 86 GHz to 90 GHz. Due to the immaturity of the fabrication process, it was not possible to obtain four working power detectors at the same chip and this limits the possible characterizations of the fabricated chips. Therefore,
the reported measurements in Fig. 5 (b) are at one baseband output. However, the fabricated circuit shows a successful proof of the six-port implementation concept.

Fig. 5. Fabricated board using T Variant at 150MHz oscillation frequency

Fig. 6. Measured spectrum of T variant at 150MHz

V. CONCLUSION

We demonstrate for the first time a fully-integrated full-fledged millimetre-wave graphene-based receiver frontend. The circuit is fabricated on thinned SiC substrate employing graphene power detectors and lowloss microstrip-based six-port junction. The proposed design approach helps to demonstrate the receiver circuit beyond $f_{\text{max}}$ of the state-of-the-art GFETs and the functionality has been verified by the demodulation of an OOK digitally modulated signal.

ACKNOWLEDGMENT

This work was financially supported by the European Commission under the projects Graphene Flagship (contract no. 696656), SPINOGRAPH (contract no. 607904).

REFERENCES