120GHz Schottky Terahertz Transceivers with Graphene FET Sub-Harmonic Mixers

Surafel Berhanu Abegaz Fetene Mulugeta Yigletu Ephrem Teshale Bekele

***Abstract*—THz communication is seen as a technology for beyond 5G wireless with both photonic and electronic approaches. Schottky diode multiplied microwave sources present a lower cost than the photonic approach but there is a tradeoff in phase noise and higher frequencies. Furthermore Graphene Field Effect Transistor (GFET) subharmonic mixers show promise for application with Schottky Barrier Diode (SBD) multipliers; however, the performance is highly dependant on the synthesis method. 120GHz double conversion transceivers were designed with Chemical Vapor Depositon (CVD) and electrochemical graphene (ECG) and evaluated in a simulation environment. 20Gbps was achieved with 16 Quadrature Amplitude Modulation (QAM) with an Error Vector Magnitude of 31.6% and 28.6% for ECG and CVD, respectively. ECG was shown to be a viable synthesis method for low cost THz front ends. In addition, the frequency range of less than 375GHz was found to be suitable when employing phase modulation with Schottky multiplied sources.**

***Index Terms*—6G, Terahertz, Graphene, Electrochemical Synthesis**

I. Introduction

With the rapid growth of data traffic globally and the emergence of 5G mobile communication, we can expect to see a range of high bitrate demanding services such as virtual reality and machine to machine communication. This increasing demand on network capacity has raised interest in beyond 5G communication. One of the envisioned technologies for 6G is Terahertz communication lying within the infrared transition frequencies between 0.1THz to 10 THz. As is well know in RF circuits and filter technologies wider bandwidth is more readily achievable with a circuit operating at a higher center frequency [1]. Resulting from the high bandwidths at THz the Shannon channel capacity indicates a higher achievable communication throughput [2]. However, THz source generation with the desirable output power and phase noise is challenging therefore gains in throughput through higher center frequencies are not trivial. THz source generation has been a challenge where there are two major approaches of which can be classified as photonic or electronic. With the photonic approach femtosecond Light Amplification Stimulated Emission Radiation (LASER)s are used to generate THz mixing products in the THz band using either nonlinear crystals, ultrafast photdiodes and also photoconductive antennas [3]. These femtosecond LASERs and accompanying systems cost in excess of a $\$10,000$ making it challenging to adopt in a ubiquitous commercial setting. With the electronic approach, Resonant Tunnel Diodes using a negative resistance and Schottky multiplication of microwave to THz provides a cost effective route [4]. Nonetheless phase noise presents a bottleneck in the performance of the multiplier based approach to THz communication as phase noise degrades by $20 \log N$ for an ideal multiplier, where N is the multiplication factor [5]. Modern digital communication systems routinely employ modulation schemes such PSK and QAM to achieve higher spectral efficiency and bits per symbol [2]. These modulation schemes and their performances are significantly impacted by the phase noise of the oscillator and to understand the implications on the design of the transceivers an investigation was pursued [6].

High performance Schottky Barrier Diodes (SBD) as used in the THz band are frequently GaAs devices due to the high electron mobility and low noise profile [3]. GaN has also been used for higher power multipliers but has a lower electron mobility hence in order to go to higher THz frequencies with less noise GaAs is preferred [7] [3]. High power local oscillators have been reported using active and passive multipliers, however, for communication using higher order modulation the phase noise is equally as important [8]. The load of the oscillator in In phase - Quadrature (de-) modulator is the mixer and serves an important role in determining noise performance of the output signal. As the output power of the multiplier stages at THz frequencies may

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not be able to forward bias a diode in a diode mixer, active mixers are used instead [5].

The THz active devices used for the mixers and amplifiers are an active area of research with InP, InGaAs and graphene being the emminent device technologies [9] [10] [11]. CMOS has also been used to extend RFIC technology into the THz band [12]. InP is yet an expensive substrate however the high frequency performance is notable with the work by Hamada et al. demonstrating the highest bitrate over a short distance using electronics [13] [14]. InGaAs HEMTs have also been used for wireless communication at 240GHz and 300GHz as a proof of concept [15] [16]. Graphene a material with outstanding electronic propeties has captured the interest of many researchers, with the highest electron mobility to date [11]. However, this electron mobility is dependant on the synthesis method of graphene, where the bottom up approaches such as CVD have been regarded as costly for mass production but presents the highest crystalline integrity [17]. Top down approaches such as solution exfoliation, liquid phase exfoliation and electrochemical exfoliation have lower costs but introduce crystalline defects that degrade performance. [17] In this research Schottky frequency multipliction in combination with subharmonic active mixers comprising Electrochemical graphene (EC) graphene and Chemical Vapor Deposition (CVD) graphene are examined for high order modulation communication transceivers.

II. Methodology

The first step was the design of a low phase noise oscillator. As a substrate RT/Duroid 5880 was used for all distributed elements. The CE3520K3 HEMT by CEL was chosen for the high gain and for the low noise figure. The GaAs HEMT was Materka modeled using the datasheet parameters to obtain alpha, Idss and threshold voltage and the S parameter file was used to fit the channel length modulation, gate drain, gate source and source drain capacitances precisely along with the parasitic inductances and contact resistances at each terminal precisely. A Colpitts architecture with parallel feedback was used and microwave oscillators at 23.23GHz, 24.4GHz and 25GHz were designed. For the analysis on THz output power vs phase noise at different frequencies only the theoretical HEMT parameters were used that is without parisitics to be device independant. A 23.13GHz was also designed for the first IF oscillator in the transceivers. To improve frequency stability on loading of the oscillator a HEMT source follower was also designed using the CE3520K3 device. Figure 1 shows the 24.4GHz oscillator.

The varactor frequency multipliers were then designed with x2 multipliers up to 400GHz using the M/A-COM MA4E1317 Schottky Barier Diode. This was done to understand and search for an optimal frequency range. The x2 multiplier used in the transceiver can be seen in Figure 2.

The third step was the design of the active fundamental and subharmonic mixers as well as amplifiers using CVD and electrochemical graphene. The CVD and electrochemical GFET subharmonic mixers can be seen in Figure 3 and Figure 4, respectively. A GaN Ka band amplifier was employed as well as a 120GHz CMOS power amplifier [18] [19]. The doping free CVD graphene FET was based on $7000\frac{cm^2}{Vs}$ carrier mobility and 73μm channel length and width whereas the electrochemical graphene had a 10μm channel length and width with a carrier mobility of $310\frac{cm^2}{Vs}$ likewise the doping density was zero. The electrochemical graphene synthesis method was based on that of Parvez et al in 2014 [20] whereas the CVD GFET was based on that of Fregonese et al in 2013 [21]. Table I summarizes the GFET parameters used.

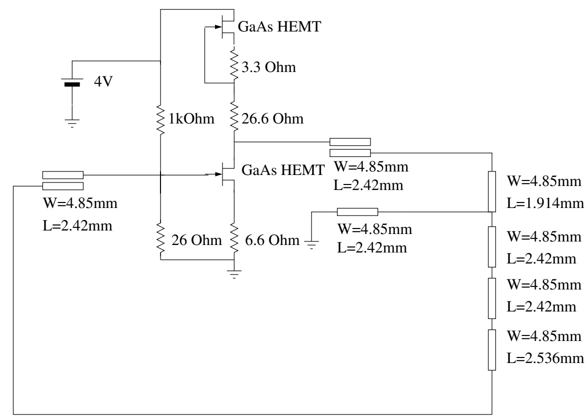

Fig. 1. Low Phase Noise 24.4GHz GaAs HEMT Oscillator

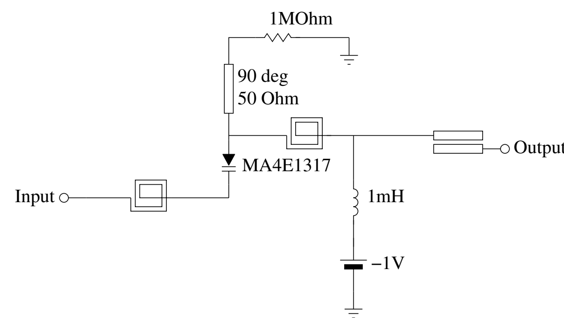

Fig. 2. Schottky Varactor Frequency Doubler - 24.4GHz to 48.8GHz

TABLE I
Graphene Model Parameters. CVD - Chemical Vapor Deposition, EC - Electrochemical.

Type	Carrier Mobility	L x W	S/D Contact Resistance
CVD	$7000\frac{cm^2}{Vs}$	73μm x 73μm	0.3 Ohm / 50 Ohm
EC	$310\frac{cm^2}{Vs}$	10μm x 10μm	0.3 Ohm / 50 Ohm

The Graphene Field Effect Transistors were used in simulation using the Fregonese model and implemented in Verilog-A [21]. A Bipolar Junction Transistor (BFP490) baseband amplifier was also designed. The transistor model parameters for the BJT can be found on the datasheet. As the fourth step,

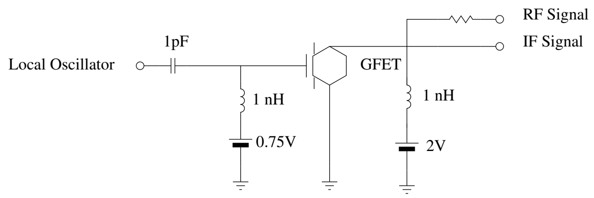

Fig. 3. 10μm Electrochemical GFET x2 Subharmonic Mixer

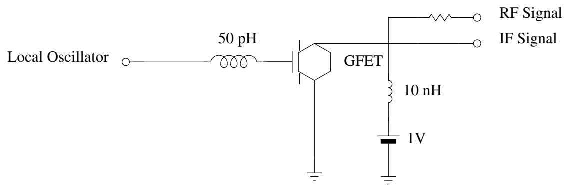

Fig. 4. 73μm CVD GFET x2 Subharmonic Mixer

a microwave diode mixer with high local oscillator rejection was designed for the double conversion architecture using HSMS-286x Schottky diode. Finally along with the frequency planning distributed stepped impedance filters were designed for both lowpass and bandpass filters. The complete double conversion transceivers front end operated at 120GHz with a bandwidth of 6GHz and a baud rate of 5Gbps and were evaluated in a simulation environment for error performance with RF/DSP co-simulation. Convolutional coding of code rate 1/2 was employed to evaluate bit error rate performance with a Viterbi decoder.

III. RESULTS AND DISCUSSION

A. THz Source Generation

The THz oscillators designed showed a power and phase noise crossover at 375GHz see Figure 5. Furthermore, the oscillator with idler at 371.7GHz can be demonstrated on a constellation plot to only support (Binary Phase Shift Keying) BPSK. The output power of 371.7GHz oscillator is also low and a mixer would further incur a significant conversion loss see Figure 5 for the output power and phase noise. Hence the operating frequency between 100GHz to 375GHz was set as the range to work with. In consideration of the sensitivity of a varactor multiplier to small changes in biasing, a single x2 was chosen to multiply 24.4GHz to 48.8GHz. The 48.8GHz source showed a very low phase noise as can be seen in Figure 6. Since the overall noise figure of a varactor multiplier increases with the number of diodes due to the series resistance only multipliers with one diode were used. Figure 7 shows the fundamental power of the CVD and EC Graphene subharmonic mixers compared with that of Zhang et al in 2016 [24].

B. THz Transceiver Error Performance

Referring to Table II, the eletrochemical Graphene FET subharmonic mixer surprisingly had good performance for a low cost design. The CVD graphene had however superior performance though less than that of the InGaAs transceivers operating at a higher frequency of 240GHz and 300GHz [16] [15]. This difference in performance is most likely due to higher coversion loss of the mixers producing lower Signal to Noise Ratio at the receiver. It was seen that 16 QAM modulation showed better error performance than BPSK, showing the benefit of using amplitude modulation in conjunction with phase modulation for this transceiver. With a rate 1/2 convolutional code the bit error rate can be made zero for all the designed transceivers. A lossless channel was used due to the communication distance targeted of less than 25m;

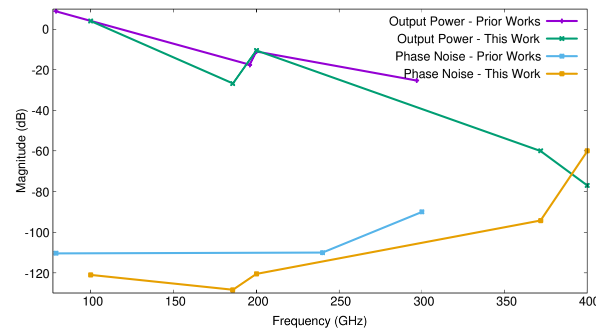

Fig. 5. THz Sources from Multipliers [22] [23] [8] [16] [15]

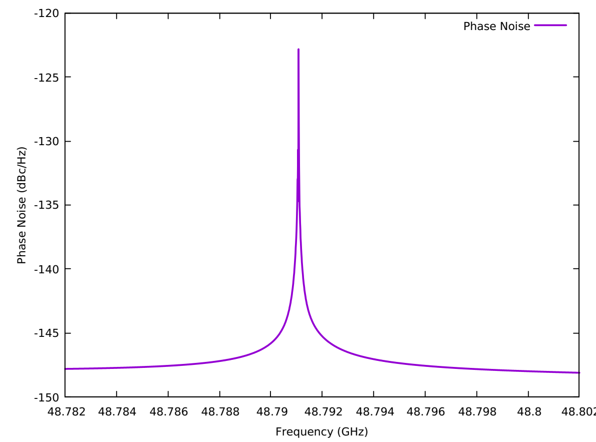

Fig. 6. 48.8GHz Oscillator Phase Noise

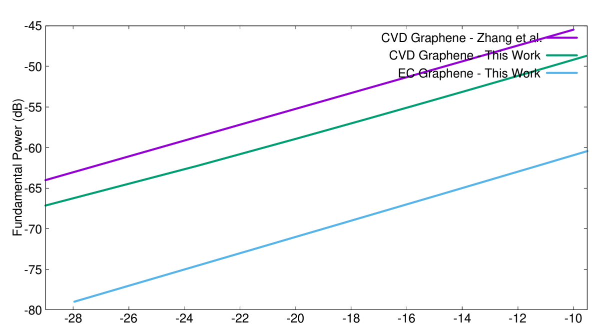

Fig. 7. x2 GFET Subharmonic Mixer Fundamental Power [24]

however, the radio propagation and antenna are for further investigation. Even though 120GHz is at an oxygen absoption peak this frequency planning can be easily adjusted for lower attenuation by using a first IF such as 10GHz.

TABLE II
ERROR PERFORMANCE

Source	THz Device	Modulation	EVM
Boes et al. (2014)	InGaAs HEMT	8PSK	21.6%
Dan et al. (2020)	InGaAs HEMT	16 QAM	15.2%
This Work	CVD Graphene	16 QAM	28.6%
This Work	EC Graphene	16 QAM	31.6%

IV. CONCLUSION

In the lower THz range of less than 375GHz highly spectral efficient modulation schemes are possible with Schottky multipliers and electrochemical graphene FET. This is promising for short range high data rate applications with a cost constraint. Amidst the abounding research on graphene synthesis it can be concluded that electrochemical synthesis is a viable method for low cost THz devices. However, InGaAs HEMT evinced better error performance than both that of CVD and electrochemical graphene FET. InGaAs can be noted nonetheless to have more semiconductor manufacturing expense. Phase noise and its affect on high order modulation transceivers is significant beyond 375GHz and is a limiting factor for the multiplier based approach.

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