A New Hot Electron Bolometer Heterodyne Detector Based On Single-Walled Carbon Nanotubes

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Abstract— **A new type of hot electron bolometer heterodyne detector is proposed that has the potential for achieving intermediate frequency bandwidths of several hundred GHz. The concept relies on experimentally measured ballistic/quasi-ballistic transport properties of single wall carbon nanotubes and the measured temperature dependence of the resistance of such tubes. The concept is related to that of Lee et al. [1] that utilized the ballistic transport in short 2DEG structures to achieve a bandwidth of 40 GHz. Receiver noise temperatures of a few thousand Kelvin, and local oscillator powers of 1 microwatt or less are estimated. This paper will explain the principle of the new detector, and give quantitative estimates of its performance.**

Index Terms—**Carbon nanotubes, hot electron bolometers, terahertz heterodyne detectors, mixers.**

I. Introduction

HOT Electron Bolometer (HEB) heterodyne detectors have a history that goes back to the InSb mixers of the 1960s [2]. Since that time, HEB heterodyne detectors (mixers) have steadily progressed in terms of desirable system properties such as noise temperature and IF bandwidth.

HEBs are two-terminal devices with a heat-able bolometer medium between ohmic contacts. It is characteristic of HEBs that the electrons in the bolometer increase their electron temperature (θ) above the lattice temperature, in response to electromagnetic radiation absorbed in the bolometer. It is also required that the bolometer resistance be a function of the electron temperature. As the bolometer is heated, it will then change its resistance, and the change in resistance is detected by DC biasing the HEB. If the radiative input is turned off, the electron temperature will relax back to the lattice temperature due to heat conduction to the thermal bath, with a characteristic time-constant, τ_{TH}. The HEB can also be operated in the heterodyne mode. Two frequencies, the signal or RF frequency (f_{RF}) and the local oscillator frequency (f_{LO}), are then applied to and absorbed by the bolometer. Such a detector can sense the difference (or intermediate) frequency ($f_{IF} = |f_{RF}-f_{LO}|$), for which the intermediate frequency (IF) bandwidth will be given by

$$B = 1/2\pi\tau_{TH} \qquad (1)$$

Table 1 reviews the main characteristics of different types of HEB mixers that have been developed.

Table 1. Characteristics of different types of HEB mixers

#	Type of HEB	Max. IF Bandwidth	Bandwidth determined by	Ref.
1	InSb	1 MHz	Carrier excitation	[2]
2	2DEG	3 GHz	Optical phonon emission	[3]
3	DHEB Superc.	10 GHz	Electron diffusion	[4,5]
4	PHEB Superc.	5 GHz	Acoustic phonon emission	[6,7]
5	2DEG	20 GHz	Electron diffusion to contacts	[8,9]
6	2DEG	40 GHz	Ballistic electron transport	[1]

HEBs have gone from being bulk type (3-D, #1) to different 2-D configurations (#2-6). The diffusion-cooled type (DHEB) has a bandwidth given by

$$BW \sim \pi D/(2L^2) \qquad (2)$$

where D is the diffusivity of the electrons and L the bolometer length [4]. Superconducting DHEBs can achieve wide bandwidth if they are made very short [5] (0.1 µm for Nb devices). In all DHEBs, the heat is transferred preferentially through diffusion of the heated electrons to the contacts. Longer (10 µm) 2DEG devices have bandwidth limited by optical phonon emission [3], but shorter 2DEG devices act as DHEBs and can achieve even wider bandwidth (20 GHz), since the diffusivity is very high (~ 2,000 cm^2/s; compare Eq. (2)) [8,9]. For very high mobility 2DEG material (>10^6 cm^2/Vs) one can reach ballistic transport conditions in short

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bolometers, and the bandwidth then varies as 1/L, instead of as $1/L^2$ (compare Eq. (2)). Lee et al. [1] measured close to 40 GHz bandwidth in such a 2DEG device that was 1.5 µm long. The electron transit velocity which can be inferred from the measurements is

$$v_t = 2\pi BL = v_F \qquad (3)$$

where v_F = 2.3 x 10^7 cm/s is the Fermi velocity of the 2D electron gas in the channel. Lee et al. [1] quote a measured temperature dependence of the device resistance, dR/dT, of 2 Ω/K. Based on HEB theory [10] one can show that the measured conversion gain of about -20 dB is consistent with this value of dR/dT. The factors that influence the conversion gain are discussed in detail in Sec. III. This gain is about 10 dB lower than for superconducting HEBs, but there are practical situations where the lower conversion gain of the 2DEG mixer is quite acceptable. The origin of the temperature-dependence of the resistance of this *fully ballistic* electron waveguide between two low-loss ohmic contacts is so far not understood. Based on the above papers, especially ref. [1,8,9], one may ask: are there other HEB bolometer media that are capable of reaching even wider bandwidths? This paper explores one such type of medium, that is known to be capable of ballistic and near-ballistic transport, that of single-wall carbon nanotubes (SWNTs). Wider bandwidths in the hundreds of GHz are indeed predicted, as the further discussion will show.

II. REVIEW OF THE TRANSPORT PROPERTIES OF SWNTs

The fabrication of SWNTs has made major advances in the last few years, and it is now possible to reproducibly fabricate and contact SWNTs which exhibit ballistic transport over fairly long lengths [11,12,13]. CNTs can be visualized as 2-D graphene (as in graphite) sheets rolled up at a number of allowed angles (different "chiralities"), see Figure 1 for an example. The energy bands in a SWNT are the result of quantization of the electrons in the *circumferential* dimension; different types of energy bands result depending on the chirality of the particular tube. Given these energy bands, we can then regard the SWNT as a one-dimensional conductor that is either metallic or semiconducting, depending on whether there are electron states near the Fermi energy or not [14]. Metallic contacts can be made to the SWNT (e.g. Pd or Ti). Close to ideal contacts, allowing a transmission probability for electrons of close to 100 %, have recently been produced [12,13]. There is also convincing evidence for ballistic transport in many cases. In general, we can find the conductance of a ballistic 1-D conductor such as a SWNT based on the Landauer model [15]. In this model, the conductance of a ballistic channel, including the effect of the contacts, is

$$G = \frac{2e^2}{h} MT \qquad (4)$$

or a maximum conductance of G_0 =1/(12.9 kΩ) per mode (for T=1). Here, we regard the channel as an electron waveguide, carrying M modes, with an average transmission probability of T between the waveguide channel(s) and the contacts. Metallic SWNTs have two degenerate bands near the Fermi level [14], i.e. M=2, leading to G(max) = 1/(6.45 kΩ).

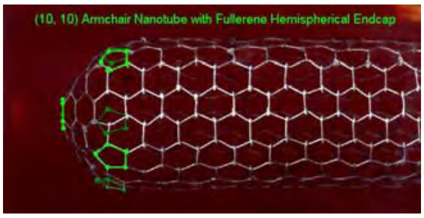

Figure 1. Structure of a so-called "arm-chair" SWNT with chirality designation (10,10).

As metioned above, SWNTs can be either metallic or semiconducting, but we concentrate our discussion on the metallic version. A typical SWNT has a diameter of 1.5 nm. The Fermi velocity is known to be considerably higher than for the 2DEG case, 8.1 x 10^7 cm/s [14]. If we insert this value in (3), and assume L = 200nm, we estimate a bandwidth of 650 GHz, more than an order of magnitude larger than for the 2DEG device. There are several different situations which may occur. For purely ballistic transport, we have already quoted the bandwidth in Eq. (3). In the case of quasi-ballistic transport, we set τ_{TH} equal to the effective transit time, t_{tr}, and calculate the bandwidth by inserting t_{tr} in (1). In surveying some of the available experimental evidence on transport in SWNTs, we will be interested in these questions:

(i) is the resistance temperature dependent;
(ii) what type of scattering occurs;

The fully ballistic regime. Kong et al. showed that the conductance of a SWNT with a length of about 200 nm depends on the temperature [12], most strongly below 100 K. For the shortest tubes, G approaches 2 G_0, consistent with M = 2 in Eq. (4). The conductance and its temperature dependence could be changed by adjusting the gate voltage and thus the Fermi energy in the SWNT. Some SWNTs showed Fabry-Perot like oscillations in their resistance, as the gate voltage was changed [12,13,16]. This and other experiments confirm that ballistic transport applies in the shortest samples. The conductance for the shortest SWNTs [12,13] measured with low voltages shows no temperature dependence.

The acoustic phonon cooling regime. A lower limit of the MFP for acoustic phonon scattering in SWNTs of 300 nm was inferred from measured I-V curves by fitting these to Monte Carlo simulations [13]. This MFP determines a minimum scattering time τ_{ap} = 370 fs.

The optical phonon cooling regime. Optical phonon emission occurs primarily at higher voltages > 0.1 V. Based on the Fermi velocity and MFP = 15 nm obtained by fitting simulations to measured I-V curves [13], we find that the scattering time is as short as 19 fs.

Effects due to defect scattering. The measured temperature dependence of the conductance for a 200nm long SWNT was explained as being due to scattering by a localized defect [12]. The assumption was that localized states within the SWNT create energy-dependent scattering, and that this effect combined with that of the temperature-dependence of the phonon populations. Defect scattering in SWNTs was also investigated in [17].

Semiconducting SWNTs. Without going into this topic in any depth, we may note that experiments again indicate the possibility of MFP's as large as 1 μm [11,17,18].

Based on the experimental evidence available so far, we can now attempt to identify ranges of parameters for which SWNT operation as HEBs would be optimized in terms of conversion gain and bandwidth. *Is it possible to obtain electron temperature-dependent resistance for a fully ballistic SWNT device?* The parallel case of the ballistic 2DEG device [1] clearly obtained such conditions. In the absence of theoretical understanding of the mechanism operating in the 2DEG device [19], we have no guidance as to whether the same mechanism may occur in a SWNT. Until such time as the theoretical situation has been cleared up, we instead propose that *the optimum condition may be one where the device has a length of only a few times the MFP*, so that even a small change in temperature may trigger the onset of a few additional collisions which may alter the current significantly and so the resistance of the nanotube. The bandwidth can be predicted by finding the transit time, and using Eq. (1). In the above regime, the bandwidth will be less than that maximally possible with purely ballistic transport, but only by a small factor. The operating temperature and the device length would be traded off to satisfy the condition of L ~ MFP. We identify three potentially useful parameter ranges below:

1) The data of Kong et al. [12] indicate a 20 % change in resistance for a change in temperature of 20 K, or 1%/K. For a certain gate voltage, a positive dR/dT was measured, and at other gate voltage values a negative dR/dT. The 2DEG device of Lee et al. [1] had dR/dT= + 2 Ω/K, or 2%/K, given that the resistance was about 100 Ω. It thus appears feasible, after optimization, to find a comparable value of dR/dT (in %/K) in SWNTs. The bias voltage at this point [12] was about 10 mV, and the main scattering mechanism invoked is defect/phonon scattering. Based on the bias voltage, the phonons involved would be acoustic phonons.

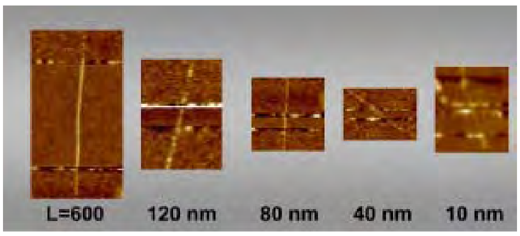

Figure 2. SWNTs of different length placed across gaps between metallic contacts. Reproduced from Javey et al. [13]

The transit time would depend on the type and location of the defect, as well as the MFP for acoustic phonon scattering. Assuming a transit time of 750 fs the bandwidth would be about 210 GHz, and the temperature of operation up to about 50 K.

2) Javey et al. [13] mention a similar temperature dependence of the resistance, up to 150 K, but with little quantitative data. Photographs of their contacted SWNTs are reproduced in Figure 2. McEuen et al. [20] review work in which a temperature dependent resistance is measured for a 1 μm long SWNT up to 290 K, but with a smaller derivative of about 0.2 %/K. Bandwidths similar to case 1) are likely.

3) If we assume optical phonon scattering, McEuen et al. [20] describe a sharply decreased conductance above 100 mV, which must be due to optical phonon emission setting in. The temperature dependence is similar to that in case 2). The optimum length for a SWNT HEB utilizing optical phonon emission would be much shorter, however (the above results [20] are for L= 1 μm).

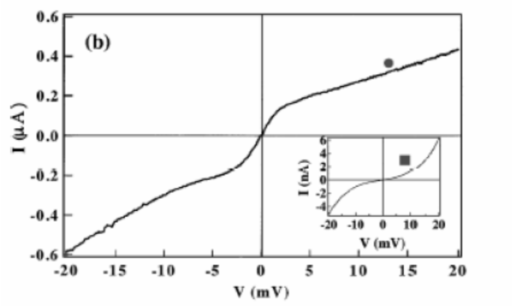

Figure 3a. IV-curve for SWNT of 300 nm length at a specific gate voltage. Reproduced from Kong et al. [12].

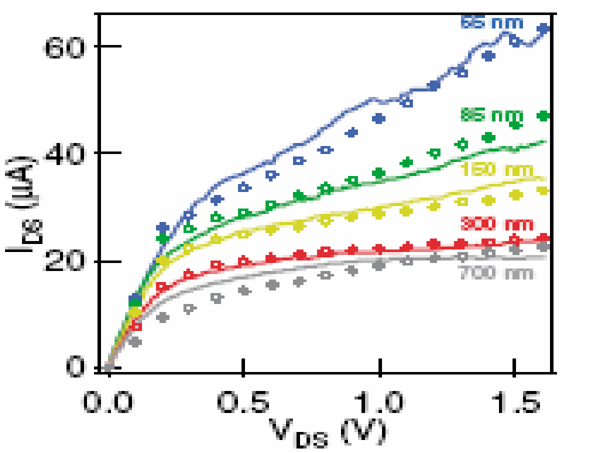

Figure 3b. IV-curves for SWNTs of different lengths in a higher voltage range than for Figure 3a. The knee in the curves is a result of optical phonon emission by the electrons. The measurements were taken at room temperature. Reproduced from Javey et al. [13].

If one were to use the principle described above of choosing L as a small number times the MFP, for example L ≈ 50 nm, one would anticipate a much steeper temperature dependence. We note that tubes down to L=10 nm have been fabricated and measured [13]. The IF bandwidth based on the transit time would theoretically be of the order of 2.5 THz, but kinetic inductance phenomena to be discussed below are predicted to limit the response to much lower frequencies.

The conversion gain can be estimated from measured I-V-curves [10]. A parameter C_0 is defined as follows

$$C_0 \equiv \frac{dR_0}{dP} = \frac{dR_0}{d\theta} \times \frac{d\theta}{dP_{DC}} \qquad (5)$$

Here, R_0 is the bolometer DC resistance = V_0/I_0 and P_{DC} the DC power dissipated in the bolometer. The AC resistance at a specific operating point (V_0,I_0) is given by $(dV/dI)_{DC}$, which can be read from an IV-curve. One can show [10] that

$$C_0 = \frac{R_0}{P_{DC}} \frac{(dV/dI)_{DC} - R_0}{(dV/dI)_{DC} + R_0} \qquad (6)$$

The most important factor in determining the conversion gain of an HEB mixer is $C_0I_0^2$. This factor is typically about 0.5 for a good superconducting PHEB mixer [7], and 0.1 to 0.2 for the 2DEG mixer [3]. It then is clear why in order to identify a promising candidate for a HEB mixer, we have been emphasizing the desirability of large values for dR/dθ. The second factor in Eq. (5) is the inverse of the thermal conductance (G) of the bolometer. We can also write G as $C_e * V/\tau_{TH}$, where C_e is the heat capacity (per unit volume) of the electron medium in the bolometer, and V the bolometer volume. We are striving to achieve a very small value for τ_{TH} in this paper, which tends to make G large. However, the effective bolometer volume of a SWNT HEB is also extremely small, which makes it feasible to still achieve the desired value of C_0, such that $C_0I_0^2$ is not much less than 1.0. The usefulness of the IV-curves[1] is that they directly tell us (through Eq. (6)) the value of the parameter C_0: a good bolometer has an IV-curve with a slope at the operating point that differs as much as possible from $1/R_0$. Such curves measured for SWNTs in [12,13] compare favorably with those of 2DEG devices which have about -18 dB to -20 dB conversion gain [1,8,9], see Figure 3 (previous page) for examples of such curves. The conclusion from evaluating cases 1) through 3) is that quasi-ballistic SWNTs could provide at least a similar conversion gain as 2DEG ballistic HEBs, with a much wider bandwidth. The optimum device length, bias voltage, LO power and temperature range must first be empirically determined through DC measurements, at different temperatures. In some cases, a gate voltage may be required for optimum operation. We should finally note that our discussion of the conversion gain assumes that the bolometer impedance is close to being matched at all three frequencies involved, the LO, RF and IF frequencies, respectively. How this may be accomplished is the topic of the next section.

[1] Strictly speaking, we should use an IV-curve under LO pumping for this evaluation. In the case of 2-DEG HEB mixers, it was shown that using the unpumped IV-curves yields close to a correct result [3].

III. CHARGE-CARRIER INERTIA AND OPTICAL AND MICROWAVE COUPLING TO SWNTs.

We would anticipate coupling electromagnetic waves to a SWNT in a manner similar to what is already a very popular method for other HEB mixers – quasi-optical coupling using a silicon lens and an antenna photo-lithographically etched on a silicon substrate, as shown in Figure 4. A typical antenna impedance is 100 Ω. We next need to estimate the equivalent circuit at terahertz frequencies for the SWNT. One-dimensional conductors have an unexpectedly large inductance, basically due to quantum-mechanical effects, the kinetic inductance, L_K. As shown in [21] and other papers referred to therein, the kinetic inductance $L_K = \hbar\pi/4e^2v_F$ or about 4nH/µm, a kinetic inductance of roughly 1 nH for a 200 nm long SWNT. At 1 THz, the inductive reactance would be 7.4 kΩ, about equal to the minimum resistance of the tube.

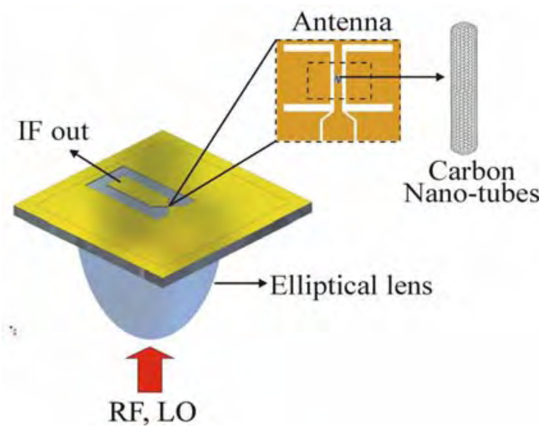

Figure 4. Quasi-Optical Coupling of a SWNT, using a twin-slot antenna and an elliptical silicon lens.

Measurements of SWNTs at GHz and THz frequencies are needed to confirm this kinetic inductance. Microwave measurements on metallic SWNTs [18] indicate that *the microwave resistance can be considerably smaller than that measured at DC*, however, and actually much smaller than the quantum resistance predicted from (4). As explained in [18], this is possible if the contacts have a large capacitance, which shorts out the contact resistance at high frequencies. This will considerably simplify the problem of impedance matching at to the bolometer.

In order to tackle the problem of coupling to the bolometer resistance, which may still be larger than the range of 50 – 100 Ω typical for antennas or microwave circuits, we can use a matching circuit such as shown in Figure 5, tuned to about 500 GHz. For the sake of illustration, we assume a bolometer resistance of 6.5 kΩ, that should be matched to a 50 Ω circuit. The frequency response is given in Figure 6. This example shows that a good match can be obtained, at the expense of a narrower bandwidth, in this case about 15 % bandwidth at the – 3dB level. It would also be very useful to measure SWNTs at lower microwave frequencies (a few GHz) in microstrip or CPW circuits. The matching circuit would in general need to take into account the kinetic inductance. Similar techniques could be used for matching at the IF frequency. In order to decrease the device resistance it is also possible to place several SWNTs parallel across the gap between the contact pads. The experimental techniques for accomplishing this are not yet well developed, however.

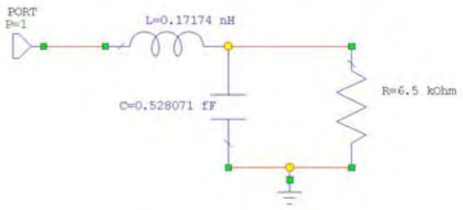

Figure 5. Matching circuit for a SWNT. Port 1 is a 50 Ω port.

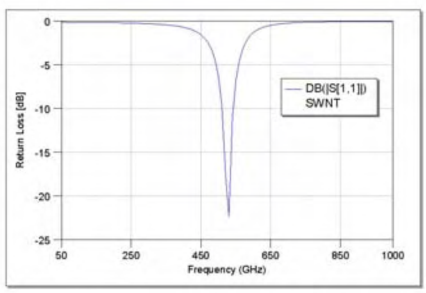

Figure 6. Frequency response of the circuit in Figure 5.

IV. PREDICTION OF THE PERFORMANCE OF A SWNT MIXER RECEIVER

In Section III we very roughly estimated a conversion loss of 20 dB (or better) for a SWNT mixer. There is again only sparse guidance available for predicting the output noise of such a mixer. However, Lee et al. [1] noted that in the ballistic regime the output noise decreased by about an order-of-magnitude, compared with the diffusion-cooled regime. A possible explanation for this observation may be that the thermal fluctuation noise (the dominant source of noise in all other HEB mixers) decreases drastically in ballistic HEBs. The remaining output noise can then be estimated as the Johnson noise at the operating temperature. The Johnson noise contribution in other HEB mixers is somewhat less than the operating (thermal bath) temperature. The actual double-sideband (DSB) mixer noise temperature will be the device output noise temperature multiplied by one half times the conversion loss. With a conversion loss of about 20 dB we estimate a DSB receiver noise temperature of < 50 x 77 K or < 4,000 K for a device operating at 77 K, and lower for lower operating temperatures. There will also be a small contribution from the IF amplifier. The receiver noise temperature may thus be somewhat higher than that of a Schottky barrier mixer. We predict a much smaller LO power for the SWNT compared with the Schottky mixer, however; at least three orders of magnitude less. This estimate is based on the fact that only the contact regions need to be heated, and these are very small (i.e. low heat capacity, as noted in Sec. III). A very rough estimate yielding a value less than $P_{LO} \leq 1$ μW can be obtained by comparison with the 2DEG HEB, which required 10 μW of LO power when operated at 77 K. We note that the contact regions in a SWNT are much smaller than those of the 2DEG HEB, so the estimate of 1 μW is likely to be on the high side. The low LO power will be advantageous in focal plane array applications, for example. We can estimate the system performance of an SWNT mixer element used for broadband imaging of a thermal object at, say, 700 GHz, by using the standard radiometer formula

$$\Delta T_{RMS} = \frac{T_{SYS}}{\sqrt{B * \tau}} = 0.5K \tag{7}$$

We inserted T_{SYS} = 5,000 K, B = 100 GHz and an integration time τ = 1 ms in (7) to arrive at this estimate of the RMS equivalent temperature fluctuations at the system input. The system can detect a temperature difference in the object comparable to a few times ΔT_{RMS}. *The above estimate would represent a state-of-the-art performance that can presently only be achieved by THz detectors cooled to liquid helium temperature* [22], if one also stipulates that the LO power (per pixel) be low enough to allow feeding a focal plane array with many elements, while employing presently available compact LO sources. Such a focal plane array would be able to perform passive thermal imaging at video rates of objects of interest for security applications as well as for medical/biological purposes.

V. CONCLUSION

We summarize the conclusions reached in this paper in Table 2 below (next page). The left column gives different potential regimes of operation, as discussed above.

There are several major challenges that must be overcome in order to realize the potential performance estimated in this paper; the primary ones have to do with finding conditions that yield a sufficiently steep temperature-dependence of the SWNT resistance, and thus a high conversion gain; impedance matching; and fabrication/placement of SWNTs. Any of the versions of SWNT HEB mixers we have discussed is likely to work over a record bandwidth for HEBs. This also creates a challenge for the IF amplifier design that must match the bandwidth of the HEB. If these challenges can be overcome, the SWNT HEB mixer has the potential for being employed in many system applications, such as THz focal plane array imagers, and broadband detectors for THz spectroscopy investigations.

Table 2. Summary of results discussed in this paper

Ballistic transport	May not show dR/dθ	BW ~600 GHz	
Acoustic phonon/defect scattering	Experim. evidence for dR/dθ	BW 100-200 GHz	Lowest LO power, lowest operating temperature
Optical phonon scattering	Experim. evidence for dR/dθ	BW < 300 GHz	Higher LO power/ operating temperature

ACKNOWLEDGMENT

I acknowledge stimulating and useful discussions related to ballistic/quasi-ballistic transport with Massimo Fischetti. I also thank Fernando Rodriguez-Morales who drew Figures 4 - 6, and performed the circuit calculations described in Sec. III.

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[19] As noted above, theoretical evaluations of dR/dT relevant to our case, assuming ballistic or quasi-ballistic transport, do not appear to have been published, so far. Unpublished work by M.Fischetti indicates a (small) negative dR/dT for the case of ballistic transport, when the current is dominated by the source function. Further theoretical work is required to clarify the features exhibited in the experimental data of [1].
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