A CNTFET Oscillator at 461 MHz

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***Abstract*— This letter presents design, implementation, and characterization of the first reported carbon nanotube field-effect transistor (CNTFET) RF oscillator. The circuit is implemented with discrete CNTFETs mounted on standard FR-4 substrate with off-the-shelf surface-mount-device components. The oscillator topology is similar to the phase shifter oscillator and uses two cascaded common source stages to provide enough gain for self-sustained and self-startup oscillation. The oscillator tank is merged with the matching network between two stages. The circuit oscillates at the frequency of 461 MHz with a phase noise of −115 dBc/Hz at 1 MHz and power consumption of 60 mW. While limited in output power by the driving capabilities of prototype CNTFETs, which still have a large density of residual metallic tubes, both power consumption and phase noise compare well with established and mature technologies. Moreover, the presented phase noise measurements provide a useful benchmark for the physical noise models being currently developed for this category of devices.**

***Index Terms*— Carbon nanotube transistors, carbon nanotube field-effect transistor (CNTFET), oscillator, phase noise.**

I. Introduction

It HAS been recently shown that the carbon nanotube field-effect transistors (CNTFETs) are emerging devices with the potential of bringing improvements into the RF frontend of highly integrated wireless communication systems. Design, implementation, and characterization of fundamental buildings blocks for such systems are necessary steps toward the experimental validation of such a promises and device-level considerations in design phase. As openly acknowledged within the device engineering community, the current state of CNTFET technologies is still far from its best possible performance, which will enable the expected benefits in RF applications [12]. Nevertheless discrete experimental devices have been fabricated for several years and offer performance sufficient for operation in the ultrahigh-frequency band of the RF spectrum. Indeed, the first amplifiers have been already demonstrated [1], [2] even up to 2 GHz. Within this frame, this letter presents the characterization of the first reported RF oscillator based on CNTFETs as active devices [13]. While the available discrete devices are early prototypes, which still suffer from limitations such as high density of metallic tubes in the channel, hysteresis, and gain degradation, direct measurements of a complete and functional circuit provide useful information toward the validation of the large-signal and noise models of the devices in the context of their intended circuit uses, as well as for essential technological optimizations. In particular, the phase noise of an oscillator is a strong function of the noise characteristics of the active device employed in the circuit, but CNTFETs—being a new technology—still lack the low-frequency noise models necessary for prediction of the oscillator phase noise. Also there are only limited publications regarding noise measurements of multitube devices [3] and none for single-tube CNTFETs. For this reason, the measurement results presented in this letter cannot be compared with circuit simulations, but rather provide an experimental data point for the validation of the required device noise model, and available device noise performance.

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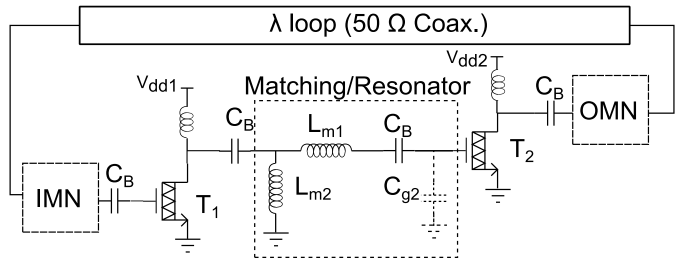

Fig. 1. Schematic of common source topology with matching network (OMN: Output matching network and IMN: Input matching network).

II. Design

The schematic of the circuit is shown in Fig. 1, it consists of cascade of two common-source stages (T_1 and T_2), connected with a narrow-band matching network, which serves at the same time as power-matching network and resonator tank. The output of the second stage is fed back to the input through two additional matching networks and a λ-long coaxial cable. This installment will satisfy the Barkhausen criterion regarding the unity closed-loop gain and zero phase at the specific frequency. Each stages consist of a common source amplifier which will contribute to the half of 360° phase shift and the coaxial cable serves to close the loop and does not affect the phase shift (mod 360°) The use of two gain stages is beneficial in providing additional gain for starting and sustaining the oscillation, as well as providing more degrees of freedom for compensating process tolerances and possible device degradation over time.

The printed circuit board (PCB) has been designed to minimize interferences from the measurement environment. We used a solid ground plane in a FR-4 PCB with dielectric thickness of 1.5 mm, multiple parallel capacitors—scaled in value—to block power supply noise, and a double braided RG142 coaxial cable to close the circuit loop.

In its open-loop configuration, the circuit is a narrow-band two-stage amplifier with input and output matching networks to a 50-Ω impedance. The circuit is implemented using discrete CNTFETs having $W = 50\ \mu$m, $L = 0.8\ \mu$m, and $t_{\mathrm{ox}} = 20$ nm with a channel consists of 2500 parallel tubes having average diameter of 1.7 nm with a ratio

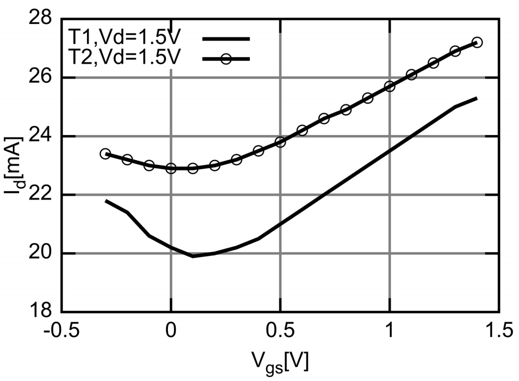

Fig. 2. DC characteristic I_d versus V_{gs} of the transistors.

of 2:1 of metallic tubes. A representative dc characteristic of these CNTFETs at employed operation point is shown in Fig. 2. For passive components we used surface-mount-device components mounted on a FR4 PCB. As the characteristics of the available CNTFETs are affected by process tolerances and bias stress [2], it is practical to characterize and tune the open-loop gain and phase before the loop is closed. This feature offers a more explicit tool for the circuit optimization, as it can be ensured that the devices are in bias conditions suitable to satisfy the oscillation condition.

The design of narrowband matching networks at microwave frequencies require fairly accurate models of active and passive devices and their interconnect parasitics. For the available CNTFETs, being those produced with a prototype process still in development, a model can at its best is customized to an individual device sample. The design of the presented circuit relied on S-parameters measurement of the devices which are directly mounted on the oscillator PCB. A second PCB sample—without CNTFETs—was used to de-embed the interconnect parasitics and extract small-signal S-parameter models for the two active devices in the circuit. The procedure has been repeated to account for drifting in the device characteristics associated with bias stress, providing a small-signal model for retuning the matching networks. This method is effective only under the assumption that the characteristics of the device that is being measured are correlated with the other device in the vicinity, on the main wafer. This is necessary because CNTFETs can be bonded only once.

The noise performance of oscillators in $1/f^2$ regime is directly proportional to the quality factor of the resonator [4]. In this design, this is determined by the low output resistance of T_1 (75 Ω) resulting from the relative high ratio of metallic CNTs in the channel. These are in parallel to the resonator and drastically reduce its Q (≈10). At frequencies close to the oscillation frequency, the phase noise behavior is dominated by the active device; for the available CNTFETs [5] traps at the CNT-oxide interface and in the gate oxide with time constants in the order of 100–1000 μs [6] are expected to define the phase noise characteristics of the oscillator near the fundamental. This claim can be validated during the measurements, which are discussed in detail in Section III.

The $f_{\max}$ of the available CNTFETs is below 1 GHz and varies from device to device, so to design a self-starting

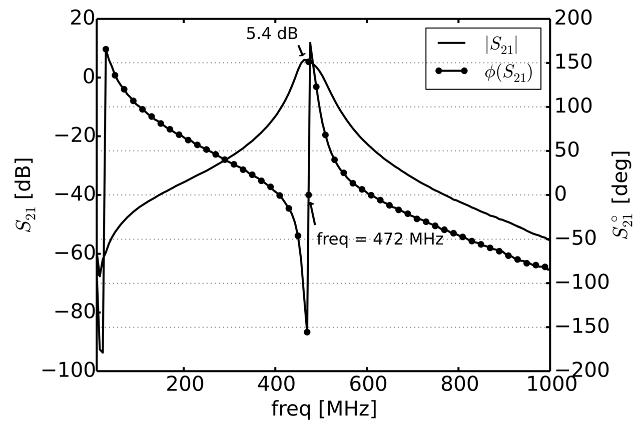

Fig. 3. Open-loop measurement, S_{21} of the circuit.

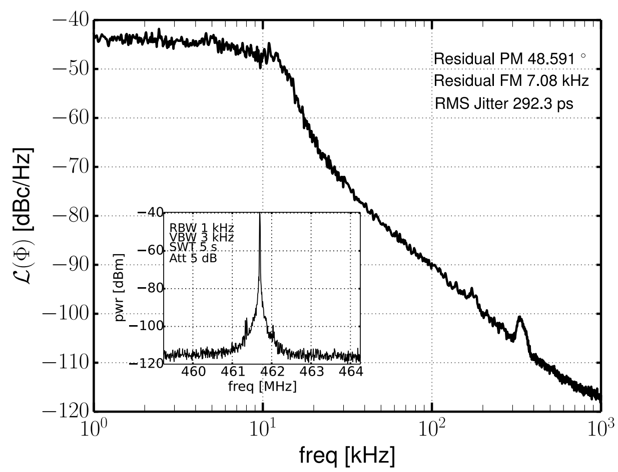

Fig. 4. Phase noise of the oscillator and the output spectrum (inset).

oscillator we set the target frequency in the subgigahertz range, with a margin of experimental confidence.

III. Measurements

The hysteresis of CNTFETs is attributed to various types of traps and requires different bias voltages for the same drain current and transconductance. For each measurement, in order to produce consistent results, this effect has been taken into account and compensated as needed. The measurements were carried out after stabilization period and during several sessions of 20’–30’ each in an ambient temperature of 23 °C to ensure the reproducibility of results. Fig. 3 shows the open-loop measurement of the two cascaded CNTFETs after matching has been carried out. T_1 was biased at $V_{ds} = 1.5$ V, $V_{gs} = 100$ mV, $I_d = 20$ mA and T_2 at $V_{ds} = 1.5$ V, $V_{gs} = 0$ V, and $I_d = 23.1$ mA. The frequency of phase crossover is 472 MHz and corresponds to a gain of 5.6 dB. To minimize losses and thus ease the oscillation, in closed-loop configuration the signal is detected by means of a near-field coupling probe, a rigid shielded copper wire shaped as coil. For measurements, the probe was held at the closest possible distance from the inductor in the input matching network, as shown in Fig. 5. The transfer function of the path from the input of the circuit to the output of this coil has been characterized with a network analyzer: this was

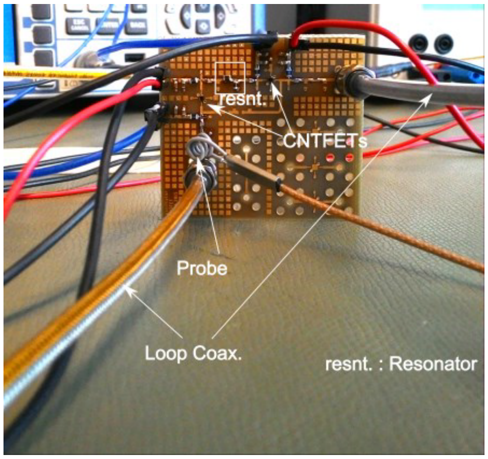

Fig. 5. Picture of the oscillator PCB and the probe.

TABLE I
COMPARISON OF THE RF CNTFET OSCILLATOR WITH EXAMPLES IN ESTABLISHED TECHNOLOGIES

Freq [MHz]	Phase noise [dBc/Hz @ 1 MHz]	Pout [dBm]	PDC [mW]	Tech	Ref.
410-470	-155	6.3	175	NA	[7]
2000	-102	11	10	Si CMOS	[8]
6400	-139	5.5	196	GaAs HBT	[9]
9200	-123	7	10	SiGe HBT	[10]
6000	-120	27	3600	GaN HEMT	[11]
460	**-116**	**-15***	**60**	**CNTFET**	**This work**

*Estimated power, by means of s-parameters measurement from the input of coaxial loop connector into the probe output.

later used to estimate the signal level in the 50 Ω section of the oscillator loop from measurements obtained through the probe with a spectrum analyzer. The measured spectrum of the closed-loop oscillation is shown in the inset of Fig. 4. Two small spikes on both sides of the fundamental are residual power supply noise, which could not be filtered further. The frequency of oscillation is 461.7 MHz, slightly lower than the phase crossover of the open-loop characteristic (Fig. 3), because of a slightly longer coaxial cable used in the loop and the nonlinearity mechanism for amplitude stabilization. Considering the measured 25 dB loss of the probe, we estimate −15 dBm of signal power in the coaxial cable, corresponding to 112 mV_{pp} on a 50 Ω characteristic impedance.

Fig. 4 shows the phase noise measurement of the oscillator, which is below −115 dBc/Hz at 1 MHz. The flat part of the graph is specific to the CNTFET devices. Without physical low-frequency noise models or measurement for multitube devices, it is not possible to attribute precisely the observed noise behavior to a specific mechanism. However, it is interesting to notice that the knee-frequency of 10 kHz matches the 1000 μs time constant of the traps, which might be playing a dominant role in shaping the phase noise. Another aspect of interest in Fig. 4 is a rather broad region where the phase noise rolls off with a slope of $1/f^3$, which indicates a large value for device flicker noise corner frequency.

IV. CONCLUSION

This letter presents the implementation and characterization of the first reported CNTFET oscillator. The available devices were fabricated with a prototype process in its early phases, still affected by a relatively large density of metallic tubes in the channel and low quality gate oxide. Nevertheless, the circuit characterization provides relevant information on the device potential, and noise characteristics in particular. Table I compares the CNTFET oscillator with the state-of-the-art in other IC technologies. While limited in output power by the driving capabilities of the available CNTFETs, which in this early process version still have a large density of residual metallic tubes, both power consumption and phase noise compare well with established and mature technologies. Improvement in the fabrication process, most importantly the reduction of metallic tubes in the channel, will improve both RF output power and dc power consumption. The noise performance, on the other hand, is still subject of active research, particularly for the low-frequency range, which is critical for the oscillator performance. In this context, the presented measurements provide a useful benchmark for the physical noise models being currently developed.

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