UHF lumped element model of a fully-inkjet-printed single-wall-carbon-nanotube-based inter-digitated electrodes breath sensor

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***Abstract*—In this effort, the authors present the first lumped element model for a fully-inkjet-printed single-wall-carbon-nanotube-based (SWCNT) inter-digitated electrode (IDE) breath sensor, in the 500-MHz to 2-GHZ frequency range. Sensible models, one intrinsic to the inkjet-printed SWCNT film, and an extrinsic (for the IDEs) were first assumed and superimposed. The models were then verified through the use of an optimization process which achieved close fitting (less than -30dB difference) with the measured detection and detection-less S-parameters of the breath sensor, while only its intrinsic parameters showing significant detection sensitivity. The suggested model offers a stepping stone for the integration of nanomaterial-based IDE sensors for low cost fully-inkjet-printed UHF sensor implementations of the Internet of Things.**

I. Introduction

The 20th century has witnessed the emergence and explosive growth of information technologies, along with their transformative impact on societies and the lives of individuals. The internet, as the main global communication network, was first accessed by user through their personal computers, and has now become pervasive in its accessibility, by means of connected portable devices. The Internet of Things (IoT) now promises to expand these technologies to create a connected world of objects, enabled with communication, processing and sensing capabilities. Yet, the fulfillment of such promises requires the emergence of disruptive technologies, which will meet—along with their ability to perform their tasks—the environmental, low cost and power autonomy requirements of ubiquitous implementation. Amongst such solutions, inkjet-printed flexible nanomaterial-based impedimetric bio-chemical sensors offer promising potential, with their capacity of detecting a wide range of chemical targets, not to mention their compatibility with functionalization-mediated selectivity and sensitivity enhancing treatments, for electronic-nose configuration implementations [1]. As a consequence, this sensor technology has been (and continues to be) a very prolific research area. Nevertheless, the study of such sensing elements in and beyond the UHF band—which could enable fully passive low cost RFID implementations—remain extremely rare [2]. In this effort, the authors introduce, for the first time, a model at UHF of an ultra-high-sensitivity SWCNT-based IDE sensing structure, applied to breath detection. First, The fabrication process of the sensor is briefly described. Then, the proposed equivalent circuit model is presented, its components optimized to fit the measured responses, and their implications discussed, before a final conclusion is drawn.

II. Sensing component fabrication

The sensing component was fully inkjet-printed on 5-mil-thick Kapton HN substrate (Dupont), using a DMP-2831 inkjet-printer from Dimatix. In order to do so, a $4\,\mathrm{mm}\times4\,\mathrm{mm}$ SWCNTs patch was first printed onto the substrate—using a custom-made ink, composed of a water dispersion of IsoNanotubes-S SWCNTs from Nanointegris. Once dried and cleaned with distilled water, an IDE structure (with $100\,\mu\mathrm{m}$-wide and $100\,\mu\mathrm{m}$-spaced fingers) and $50\,\Omega$ feeding lines were printed, respectively, onto and from the SWCNT film, using a silver nanoparticle ink from Suntronic. Finally, the ink was dried and sintered, and copper tape attached to the back of the substrate, to create a ground plane. For measurement and characterization purposes, the component was interfaced with end-launch connectors (Fig. 1).

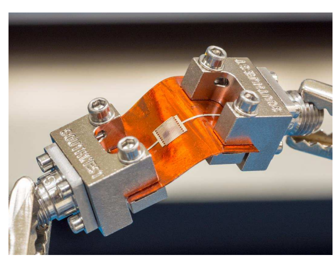

Fig. 1. Picture of the flexible, fully inkjet-printed SWCNT-based IDE structure

III. Component model

A. Model determination

Over a sufficiently small frequency range (which is the practical case for most single-band applications), many different

TABLE I
OPTIMIZED COMPONENT VALUES OF THE EQUIVALENT CIRCUIT IN INITIAL AND DETECTION STATES, AND THEIR RELATIVE VARIATIONS

Case	Components					
	R_{CNT} (Ω)	L_{CNT} (nH)	C_{series} (pF)	$C_{ext,end}$ (pF)	R_{ext} (Ω)	l (mm)
Initial	25.1	1.29	3.86	1.31	7.36	3.14
Detection	40	1.81	2.60	1.32	7.21	3.12
Relative change (%)	59	41	-33	0.8	-2	-0.3

equivalent components models may provide an accurate way of describing the behavior of the modeled element. Nevertheless, due to the scalability of such IDE structures, the goal of the approach taken in this effort was to provide an equivalent circuit which would also bring some insight into the intrinsic electrical characteristics of the inkjet-printed SWCNT film. As a consequence two probable models were assumed and superimposed (Fig. 2): an equivalent circuit of the "extrinsic" properties of the IDEs, and a lumped component model of the SWCNT film. In addition, due to the small electrical length of the IDE fingers, the effect of propagation in the IDE structure was not taken into account in the model. The extrinsic electrode-related model consists of feed lines, followed by a series resistors —to account for conductor losses in the fingers—and shunt and series capacitors, that (respectively) model the end-of-finger fringe capacitance, and inter-electrode capacitive coupling. The inkjet-printed SWCNT film was initially modeled as series inductor and resistor.

B. Parameter fitting

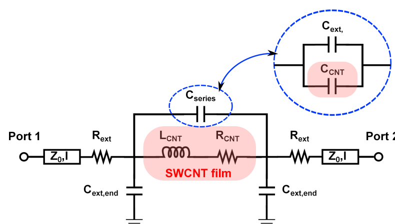

Fig. 2. Equivalent circuit of the sensing IDE structure

The sensing component was connected to a R&S ZVA8 VNA and measured (in the $500\,\mathrm{MHz}$ to $2\,\mathrm{GHz}$ range) ; once initially (initial state), and a second time, after blowing onto the sensor for one second (detection state). Subsequently the measured S-parameters were used as reference for model fitting. The fitting was conducted by solving an optimization problem—over the space of the component values of the pre-determined equivalent circuit topology—whose goal was to minimize the magnitude of the complex distance (over the entire frequency range) between all the measured S-parameters, and that of the simulated model. In both cases (initial and detection state), an absolute maximum distance of less than $-30\,\mathrm{dB}$ was achieved, therefore demonstrating the high performance of the model. When plotted next to each other (as on Fig. 3), the S-parameters of the model and that of the measured sensor, indeed, show very good agreement.

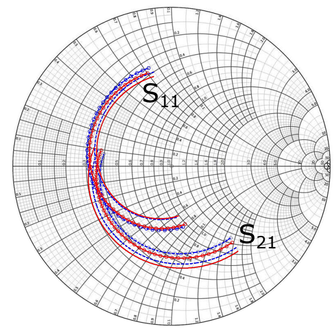

Fig. 3. Measured (full red) and modeled (dashed blue) S-parameters of sensor, in initial (○ marker) and detection (no marker) states

The two sets of parameters, determined by the optimizer, are shown on Table I. As we can see, the parameters associated with the inkjet-printed SWCNT film show large variations upon detection, while the assumed extrinsic parameters—with the exception of C_{series} —show very small variations. As a consequence, the model was revised by splitting C_{series} into an extrinsic series capacitor (C_{ext}), and a SWCNT-induced capacitor (C_{CNT}), therefore providing two fully independent models: intrinsic detection-sensitive, and extrinsinc detection-insensitive.

IV. CONCLUSION

The model introduced in this effort provides a scalable approach for the accurate modeling and integration of high performance SWCNT IDE sensors in the UHF frequency band, which is an essential step towards the emergence of truly low cost and fully-inkjet-printable chemical sensors for Smart Skins and the Internet of Things.

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