

## Research Article

# Towards a Carbon Nanotube Intermodulation Product Sensor for Nonlinear Energy Harvesting

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It is critically important in designing RF receiver front ends to handle high power jammers and other strong interferers. Instead of blocking incoming energy or dissipating it as heat, we investigate the possibility of redirecting that energy for harvesting and storage. The approach is based on channelizing a high power signal into a previously unknown circuit element which serves as a passive intermodulation device. This intermodulation component must produce a hysteretic current-voltage curve to be useful as an energy harvester. Here we demonstrate a method by which carbon nanotube transistors produce the necessary hysteretic  $I$ - $V$  curves. Such devices can be tailored to the desired frequency by introducing functional groups to the nanotubes. These effects controllably enhance the desired behavior, namely, hysteretic nonlinearity in the transistors'  $I$ - $V$  characteristic. Combining these components with an RF energy harvester may one day enable the reuse of inbound jamming energy for standard back end radio components.

## 1. Introduction

Wideband receiver designs used in command and control systems may be susceptible to high level, off-tuned interference [1, 2]. Specifically, a high power jammer or other sources of strong interfering signals in nearby frequencies will overload the amplifier and limiter stages in the front end of such communications receivers. For example, frequency hopping receivers in very close proximity to multiple high-powered transmitters have their communication range reduced significantly [3–5]. This range reduction is primarily due to nonlinear effects in the front end of the receiver, whereby diodes near the receiver's antenna port typically used for power limiting or circuit switching begin to behave as mixers [6]. Mixing leads to significant intermodulation products in virtually all channels [7].

Typically the effects of an interferer are limited by channelizing the signal [8, 9]. One such technology is the Comb Limiter Combiner (CLiC) filter, which is able to neutralize a strong interferer by distributing an antenna signal to a bank of input bandpass filters [10, 11]. The input bandpass filters

have contiguous passbands that comprise the total receiver bandwidth. Each input bandpass filter is connected to a limiter having a threshold equal to the limiting threshold of the receiver, while each limiter is connected to an output bandpass filter similar to the corresponding input bandpass filter to remove out-of-band intermodulation products. The bank of output bandpass filters is connected to an output signal coupler for coupling to the front end of the receiver. The advantage of the CLiC is that intermodulation products are restricted to the passband of a single bandpass filter. However, it is ultimately limited by heat buildup and power handling of the individual filter elements [12, 13].

Passive intermodulators, such as rusty bolts on a ship, can form isolated resonant cavities for the production of intermodulation products, which then reradiate back into the original antenna or circuit (Figure 1(c)) [14]. A hysteretic current-voltage characteristic is required for a resonator to produce intermodulation products [15, 16]. When a two-tone, high power signal interacts within the cavity, the tones interfere in a manner dependent on both the magnitude and the frequency of the tones. If the  $I$ - $V$  were nonhysteretic

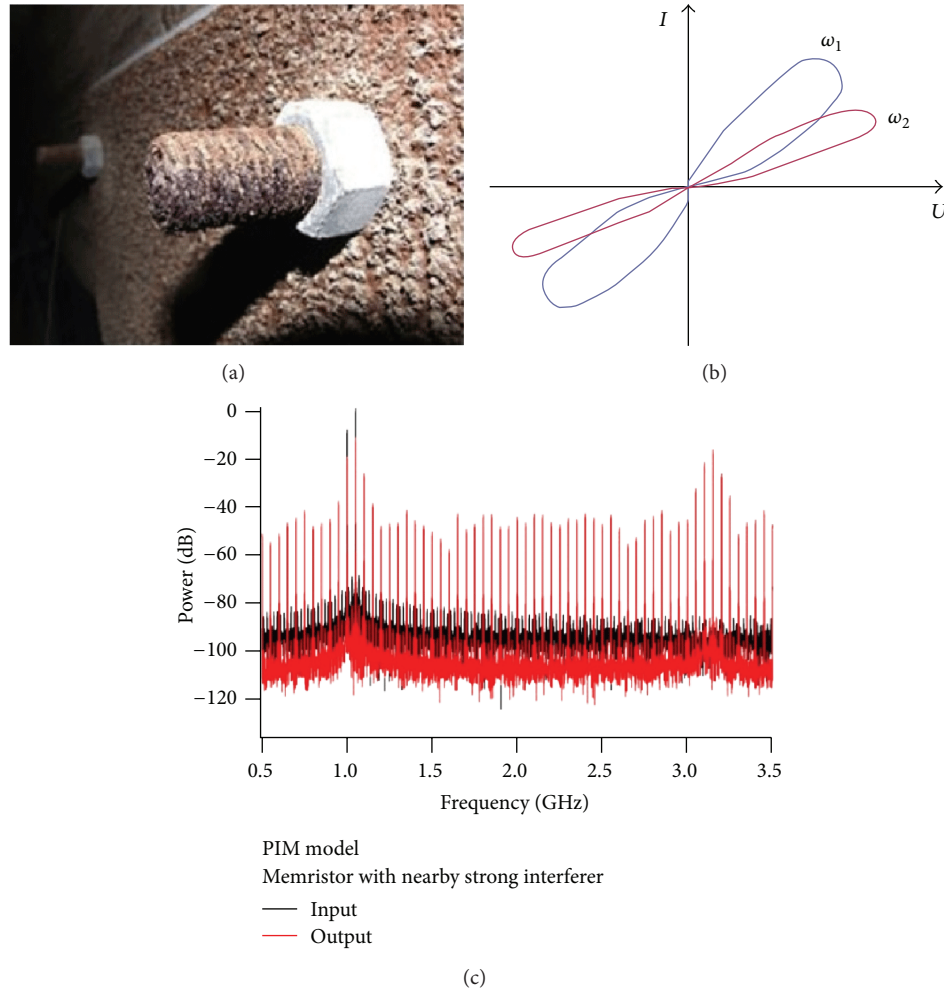


FIGURE 1: (a) Rusty bolt on a ship hull, which can act as a passive intermodulator. (b) Current-voltage characteristic of a memristor, a nonlinear circuit element, displaying hysteretic, frequency-dependent behavior. Such properties are critical for creating intermodulation products. (c) A simulated two-tone input produces strong intermodulation products at many different frequencies due to the nonlinear memristor circuit element.

(i.e., a resistor), the tones would not self-interfere and hence could not produce intermodulation products.

Carbon nanotube-based devices may help to mitigate the effects of high power jamming by intentionally shifting some of that energy into unused frequency bands in the form of out-of-band intermodulation products [17]. Further, instead of blocking the out-of-band energy or dissipating it as heat in filters or amplifiers, an alternative approach is to harvest the energy for powering low profile devices [18, 19]. Carbon nanotubes have unique electronic and optoelectronic properties which make them viable candidates for producing out-of-band intermodulation products, which can then be routed into an energy recycler [20]. The first step in producing such a device is to create a circuit element that displays a hysteretic, controllable current-voltage trace. The hysteretic current-voltage curve produced by applying a slowly varying AC back gate voltage to a carbon nanotube transistor is just such a component to allow for selective frequency shifting of high power signals in a nondissipative manner. Chemical

defects made to the nanotube sidewall change the resistance of the device, thus modifying the hysteretic current-voltage characteristic in a controllable manner. The carbon nanotube intermodulation (CNTIM) system could serve as a replacement for the traditional CLiC limiter circuit, where high power signals are splattered to intermodulation frequencies with the CNTIM device, and the resulting energy is given a low resistance path to a power collector through low pass and high pass filters.

## 2. Materials and Methods

Experiments were performed using carbon nanotubes grown by chemical vapor deposition (CVD) according to a published recipe [21]. Briefly, iron nitrate was dissolved in isopropanol and deposited using a spinner onto a 500 nm  $\text{SiO}_2/\text{Si}$  wafer. As the temperature in the CVD furnace increased to 900°C, the iron coalesced into nanoparticles, which served as

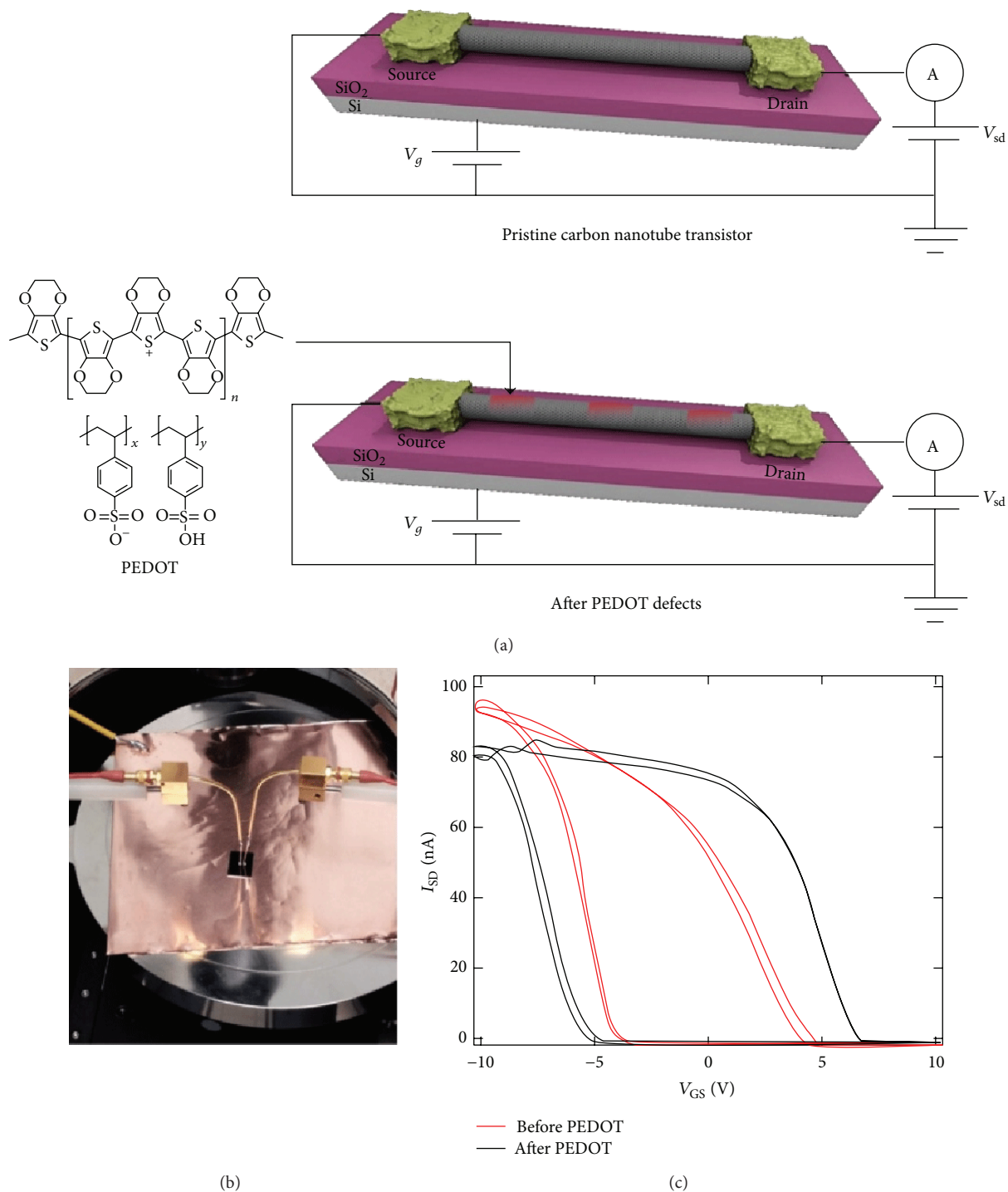


FIGURE 2: (a) Carbon nanotube transistor before and after PEDOT : PSS attachment. The chemical locally gates the nanotube transistor (shown in red) resulting in a change in the electronic transport properties. (b) Carbon nanotube transistor being measured on a probe station. (c) Source-drain current as a function of the back gate voltage for a carbon nanotube transistor before and after PEDOT : PSS functionalization. The ON state current decreases and the transistor turnoff voltage shifts to the left, indicating the presence of a charged chemical moiety.

the catalyst for the decomposition of methane and the formation of carbon nanotubes. Source and drain electrodes were patterned such that each transistor device consisted of a sparse network of roughly twenty nanotubes. Responses of

a nanotube ensemble have been shown to be more robust than single nanotube devices [22, 23]. Chemical defects were created by spin casting a solution of PEDOT : PSS diluted 1 : 9 with deionized water at 3000 rpm for 1 min.

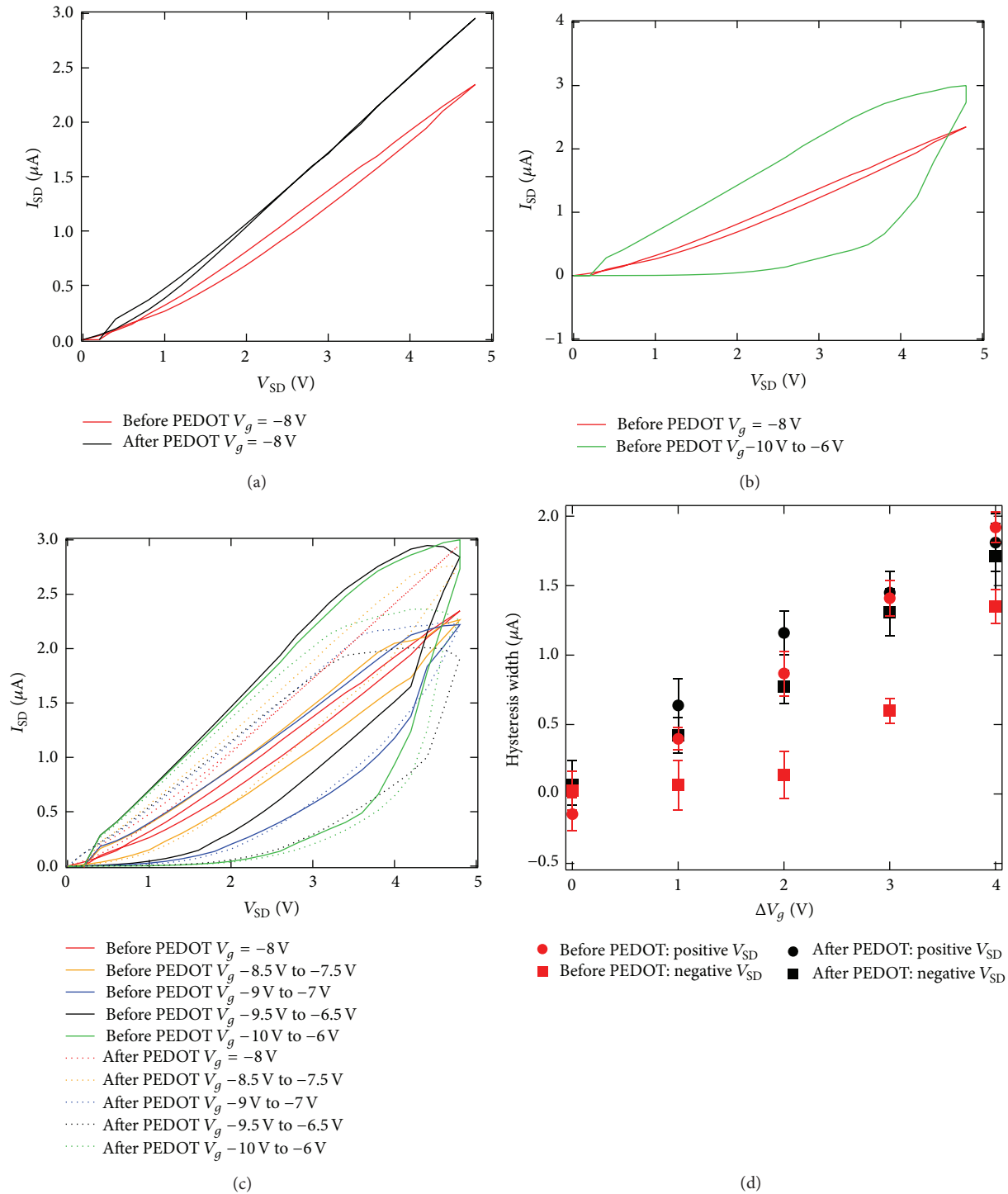


FIGURE 3: (a) Current-voltage ( $I$ - $V$ ) measurement of a single device before and after PEDOT : PSS functionalization. (b)  $I$ - $V$  measurement of a single device taken with the back gate fixed (sweep frequency = 0 Hz) and with an AC voltage applied (1 Hz). (c)  $I$ - $V$  curves taken before and after chemical functionalization on a single device with varying magnitudes of back gate modulation. (d) Summary plot of the hysteresis width as a function of the applied back gate modulation.

### 3. Results and Discussion

At this concentration, the density of PEDOT : PSS on the surface was insufficient to be conductive on its own, but enough

molecules remained to coat the nanotube surface via  $\pi$ - $\pi$  stacking (Figure 2(a)). Several carbon nanotube transistors were measured on a homebuilt probe station (Figure 2(b)) and the DC source-drain current as a function of applied back

gate voltage confirms the attachment of the PEDOT:PSS compound. A CNT device is depicted in Figure 2(c) with an ON state current of 92 nA and an ON/OFF current ratio greater than 4200. After PEDOT:PSS functionalization, the current is reduced by ~10–15% and the turnoff voltage of the transistor typically decreases 1.0–1.5 V. The current reduction is likely due to the PEDOT:PSS acting as a scattering center for charge carriers in the nanotube while also locally gating the device. Indeed, the negative charges of the sulfonate groups would be protonated at the SiO<sub>2</sub>/water interfacial pH of 5, leaving only the positive charge of the ethylenedioxythiophene group which would produce the gating effects observed [24, 25].

Measurements of the  $I_{sd}$ - $V_{sd}$  curve for a given carbon nanotube transistor were taken with the gate voltage ( $V_g$ ) fixed at -10 V so that the device was in the conductive state. As demonstrated in Figure 3(a), there is not any significant hysteresis in the  $I$ - $V$  curve for either the pristine device or the PEDOT:PSS coated device. However, there is a clear rotation in the  $I$ - $V$  plane due to the new device resistance after attachment of PEDOT:PSS. To control the hysteresis width, we applied a time varying back gate voltage with known amplitude where the time scale of the gate voltage cycling is comparable to the measurement sweep rate. A back gate swing of 4 V caused a widening of the hysteresis by ~1.5  $\mu$ A (Figure 3(b)). The amount of hysteresis induced is controllable through the magnitude of the back gate swing as well as the presence or absence of chemical functionalization (Figure 3(c)). A concise summary of the relation between gate swing and hysteresis width for 12 devices is plotted in Figure 3(d). Materials with  $I_{sd}$ - $V_{sd}$  curves like those generated in Figure 3(c) are suitable for producing intermodulation products as discussed. By applying a high power signal to the input of the carbon nanotube transistor, the resulting source-drain current should contain energy at mixed frequencies. The input power required for this device is the bias voltage (1  $\mu$ W). A typical linear amplifier produces as much as 5 mW of energy at off-resonant frequencies, meaning the potential gain in energy for this device configuration is a factor of 5000.

#### 4. Conclusions

In sum, we have demonstrated a nonlinear circuit element made from carbon nanotube transistors which display hysteretic effects. This type of hysteretic circuit element is required to produce intermodulation products from a high power input signal. By introducing a chemical defect, we can change the device resistance and access more of the parameter space for tailoring the sensor to a particular frequency band if necessary. These devices may one day be incorporated into a system like the CLiC channelizer for energy harvesting in unused frequency bands, thus extending the lifetime of low power devices in the field such as security alarms, microphones, power meters, and low power radar.

#### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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#### References

- [1] R. Gummadi, D. Wetherall, B. Greenstein, and S. Seshan, "Understanding and mitigating the impact of RF interference on 802.11 networks," *ACM SIGCOMM Computer Communication Review*, vol. 37, pp. 385–396, 2007.
- [2] F. J. Block, "Performance of wideband digital receivers in jamming," in *Proceedings of the IEEE Military Communications Conference (MILCOM '06)*, October 2006.
- [3] P. Popovski, H. Yomo, and R. Prasad, "Strategies for adaptive frequency hopping in the unlicensed bands," *IEEE Wireless Communications*, vol. 13, no. 6, pp. 60–67, 2006.
- [4] J. Zander, "Adaptive frequency hopping in HF communications," in *Proceedings of the IEEE Military Communications Conference (MILCOM '93)*, vol. 2, October 1993.
- [5] M. R. Souryal, D. R. Novotny, D. G. Kuester, J. R. Guerrieri, and K. A. Remley, "Impact of RF interference between a passive RFID system and a frequency hopping communications system in the 900 MHz ISM band," in *Proceedings of the IEEE International Symposium on Electromagnetic Compatibility (EMC '10)*, pp. 495–500, USA, July 2010.
- [6] R. D. Hayes, "Electronic warfare and countermeasures," in *The RF and Microwave Handbook*, M. Golio, Ed., Engineering, chapter 2, pp. 196–216, CRC Press, 1st edition, 2001.
- [7] D. Girbau, N. Otegi, L. Pradell, and A. Lázaro, "Study of intermodulation in RF MEMS variable capacitors," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, no. 3, pp. 1120–1130, 2006.
- [8] R. Gomez-Garcia, "RF and IF channelizers for wide-band sensing in cognitive/software-defined-radio receivers," in *Proceedings of the European Microwave Conference (EuMC '12)*, pp. 1158–1161, June 2012.
- [9] A. P. Vinod, E. M.-K. Lai, A. B. Premkumar, and C. T. Lau, "A reconfigurable multi-standard channelizer using QMF trees for software radio receivers," in *Proceedings of the 14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '03)*, vol. 1, pp. 119–123, September 2003.
- [10] M. A. Maiuzzo, S. T. Li, J. W. Rockway, J. H. Schukantz, and D. W. Tam, "Comb limiter combiner for frequency-hopped communications," US 6,549,560 B12003.
- [11] R. Adams, T. Harwood, and M. Maiuzzo, "An innovative signal distribution system that allows EMI free communications for navy ships," in *Proceedings of the IEEE Military Communications Conference (MILCOM '08)*, pp. 1–4, IEEE, San Diego, Calif, USA, November 2008.
- [12] P. Blondy and D. Peroulis, "Handling RF power: the latest advances in RF-MEMS tunable filters," *IEEE Microwave Magazine*, vol. 14, no. 1, pp. 24–38, 2013.
- [13] B. Pillans, J. Kleber, C. Goldsmith, and M. Eberly, "RF power handling of capacitive RF MEMS devices," in *Proceedings of the IEEE MTT-S International Microwave Symposium Digest*, vol. 1 of Cat. No. 02CH37278, pp. 329–332, June 2002.
- [14] P. Lui, "Passive intermodulation interference in communication systems," *Electronics & Communications Engineering Journal*, vol. 2, no. 3, pp. 109–118, 1990.

- [15] J. Henrie, A. Christianson, and W. J. Chappell, "Engineered passive nonlinearities for broadband passive intermodulation distortion mitigation," *IEEE Microwave and Wireless Components Letters*, vol. 19, no. 10, pp. 614–616, 2009.
- [16] A. Christianson and W. Chappell, "Measurement of ultra low passive intermodulation with ability to separate current/voltage induced nonlinearities," in *Proceedings of the IEEE MTT-S International Microwave Symposium (IMS '09)*, pp. 1301–1304, June 2009.
- [17] M. T. Abuelma'atti, "Harmonic and intermodulation performance of carbon nanotube field-effect transistor-based and single-electron tunnelling transistor-based inverting amplifiers," *International Journal of Electronics*, vol. 98, no. 7, pp. 847–861, 2011.
- [18] M. Alexe, S. Senz, M. A. Schubert, D. Hesse, and U. Gösele, "Energy harvesting using nanowires?" *Advanced Materials*, vol. 20, no. 21, pp. 4021–4026, 2008.
- [19] M. Rahimi, H. Shah, G. S. Sukhatme, J. Heideman, and D. Estrin, "Studying the feasibility of energy harvesting in a mobile sensor network," in *Proceedings of the IEEE International Conference on Robotics and Automation*, vol. 1 of (Cat. No.03CH37422), Taipei, Taiwan, May 2003.
- [20] A. A. Pesetski, J. E. Baumgardner, E. Folk, J. X. Przybysz, J. D. Adam, and H. Zhang, "Carbon nanotube field-effect transistor operation at microwave frequencies," *Applied Physics Letters*, vol. 88, no. 11, Article ID 113103, 2006.
- [21] M. B. Lerner, J. D'Souza, T. Pazina et al., "Hybrids of a genetically engineered antibody and a carbon nanotube transistor for detection of prostate cancer biomarkers," *ACS Nano*, vol. 6, no. 6, pp. 5143–5149, 2012.
- [22] N. J. Kybert, M. B. Lerner, J. S. Yodh, G. Preti, and A. T. C. Johnson, "Differentiation of complex vapor mixtures using versatile DNA-carbon nanotube chemical sensor arrays," *ACS Nano*, vol. 7, no. 3, pp. 2800–2807, 2013.
- [23] M. B. Lerner, N. Kybert, R. Mendoza, R. Villechenon, M. A. Bonilla Lopez, and A. T. Charlie Johnson, "Scalable, non-invasive glucose sensor based on boronic acid functionalized carbon nanotube transistors," *Applied Physics Letters*, vol. 102, no. 18, Article ID 183113, 2013.
- [24] J. P. O'Reilly, C. P. Butts, I. A. I'Anson, and A. M. Shaw, "Interfacial pH at an isolated silica-water surface," *Journal of the American Chemical Society*, vol. 127, no. 6, pp. 1632–1633, 2005.
- [25] M. B. Lerner, J. M. Reszczenski, A. Amin, R. R. Johnson, J. I. Goldsmith, and A. T. C. Johnson, "Toward quantifying the electrostatic transduction mechanism in carbon nanotube molecular sensors," *Journal of the American Chemical Society*, vol. 134, no. 35, pp. 14318–14321, 2012.

