Inkjet-Printed Broadband/Multiband Wearable and Conformal Antennas and Modules

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ABSTRACT

In this paper, several inkjet-printed wearable and conformal antennas and modules are introduced. An inkjet-printed ammonia gas sensor using printed carbon nanotubes (CNT) is designed, fabricated, and measured. The CNT is functionalized to increase sensitivity to ammonia gas, and the change in the impedance of the CNT correlates to a shift in the resonance frequency of a patch antenna. An inkjet-printed electromagnetic bandgap-backed (EBG) RFID tag has been designed and tested for wearable and metal mount applications. Measurements show that for on-body and on-metal measurements, the read range increases by approximately a factor of 2. Lastly, meander inductors are demonstrated utilizing inkjet-printing on organic paper substrates. Quality factors of up to 25, which is an order of magnitude greater than previous works, and inductance values of up to 8 nH are achieved. There are numerous applications for each of these antennas and modules in wearable electronics, deployable gas sensors for military applications, and flexible electronics.

Keywords: nanotechnology, wearable electronics, inkjet-printed, flexible electronics, printed electronics

1 INTRODUCTION

Printed electronics have shown tremendous growth in recent years, and the demand for faster, smaller, cheaper, and more efficient printed devices is ever increasing. Inkjet printing is a technology which has demonstrated the ability to fabricate electronic components in a rapid, additive manner which can be scaled to mass production in roll-to-roll processing to meet these needs. Applications include displays, disposable electronics applications such as RFID tags, antennas, chemical sensors, biosensors, inductors, capacitors, and transistors.

Chemical gas sensors have been designed and developed by integrating nanotechnology, wireless communication, and inkjet printing fabrication.[1],[2] Carbon nanotubes (CNT) are the nanomaterial have been inkjet-printed onto a printed antenna, all on a flexible organic substrate.[3] The CNTs have been functionalized with poly-aminobenzene sulfonic acid (PABS), so that they are highly sensitive to ammonia gas. The ammonia molecules adhere onto the functionalized CNT, which changes the impedance. This change in impedance shifts the frequency of the antenna that the CNT has been printed onto, thereby indicating the presence of ammonia gas. These sensors can be used in applications such as detecting gas leaks as well as detecting improvised explosive devices (IEDs).

The prospects of printed electronics is very high in the healthcare industry, where flexible wireless biosensors can be fabricated for point-of-care wireless health monitoring. Typically antennas lose significant gain when placed on the human body due to the conductivity of the body. These challenges have been met by the use of electromagnetic bandgap (EBG) antennas that are inkjet-printed on an organic substrate and placed on the human body. The use of EBG antennas improves the gain by close to two-fold, when compared to its performance in free space. RFIDs integrated with wearable antennas is a major area of research for both military and logistics. [4,5]

For a fully inkjet printed system, both passives such as inductors, capacitors, and resistors, as well as actives such as transistors is necessary. It has been demonstrated that magnetic iron and cobalt nanomaterial has been printed with inductors to increase the inductance.[7-9] Dielectrics have also been printed with capacitors to increase the capacitance. Even transistors are now printed to enable a fully functional wireless circuit, that is entirely inkjet printed on paper or plastic or other flexible substrates.

This paper introduces the devices that have been printed for wireless sensors, wearable antennas, and printed inductors. Due to the extreme low-cost of fabrication, low profile, light weight, and flexibility, printed electronics can meet the demands in many different fields, including healthcare, military, sensing, and communication.

2 INKJET-PRINTED ELECTRONICS

A Fujifilm Dimatix materials printer was used to fabricate the inkjet-printed wearable and conformal antennas and modules. For the conductor, a Cabot conductive ink CCI-300 was used. The viscosity was 11-15 cP, surface tension 30-33 mN/m at 25oC. The silver solid loading was 19-21% in weight, and the density was 1.23-1.24 g/ml. A cartridge was filled with the CCI-300 ink as shown in Figure x. The organic paper substrate was electrically characterized up to 10 GHz to find the dielectric constant of the paper for the antenna and passive rf modules. The conductivity of the ink is 4.7×10^6 [S/m].

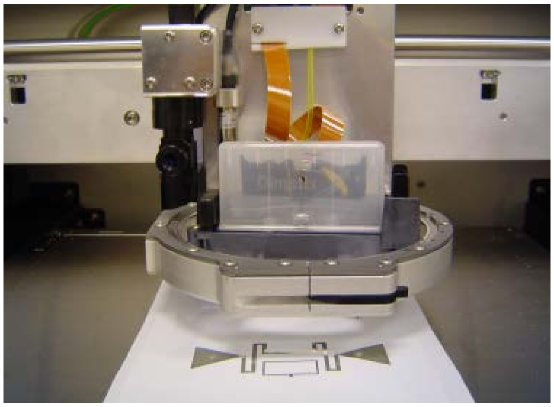

Figure 1. Fujifilm Dimatix materials printer printing conductive ink on paper substrate.

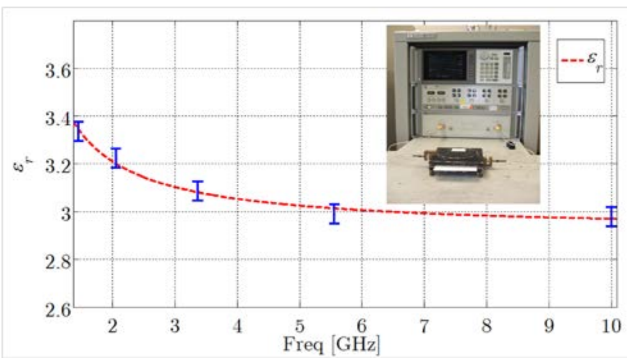

Figure 2. Dielectric constant characterization photopaper up to 10 GHz.

The substrate material, which was Kodak photopaper, was electrically characterized for the dielectric constant using a ring resonator. The relative permittivity ranged from 3.4 to 3 depending on the frequency range from 1GHz to 10 GHz. The loss tangent was approximately 0.077 at 1GHz. Based on these electrical characteristics, the following antennas and RF modules were designed and simulated in the CST electromagnetic simulation software and fabricated using this inkjet-printing technology.

3 CNT-BASED WIRELESS AMMONIA GAS SENSOR

Carbon nanotubes (CNT) have certain sensitivity to various gases and humidity. Using specially functionalized carbon nanotubes where the CNT is coated with poly aminobenze sulfonic acid (PABS), the CNT would become much more sensitive to ammonia gas based on the strong binding of NH_4 to SO_3 as shown in Figure 3. First, the high frequency electrical properties of the CNT was extracted by printing the CNT using the Dimatix printer onto the characterized photopaper substrate. De-embedding the effects of the sma connector and transmission lines, the CNT had resistance of 50 Ω and reactance of –j9 Ω, as shown in Figure 4. Exposing the CNT to ammonia gas increased the resistance to 100 Ω and reactance to -j23 Ω. Therefore a resistor in parallel with a capacitor was used as a discrete component model for the printed CNT.

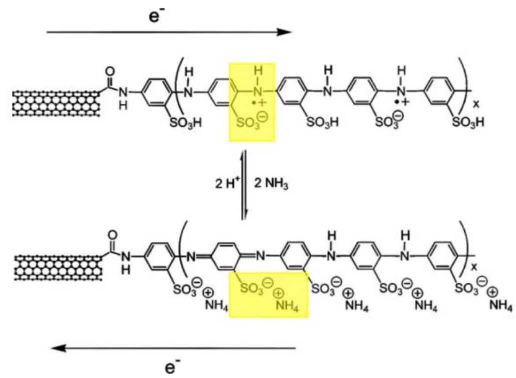

Figure 3. Mechanism of interaction of PABS-SWNT with NH. The arrows indicate charge transfer between SWNT and PABS. [3]

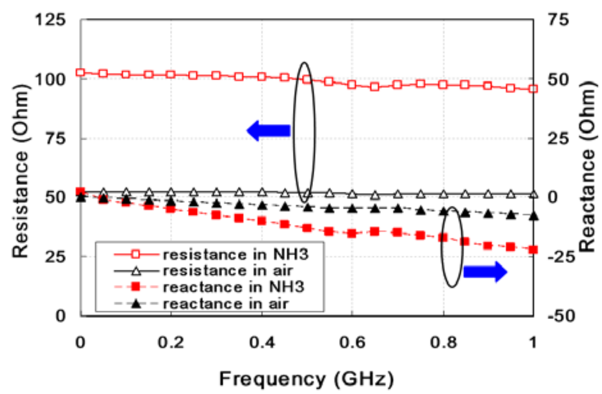

Figure 4. High frequency impedance characterization of CNT in air and in ammonia gas.

To be able to wirelessly sense the presence of ammonia gas, a patch antenna loaded with the CNT was designed. The radiation pattern was unidirectional, increasing the read range. The CNT was loaded in a gap in a microstrip transmission as shown in Figure 5.

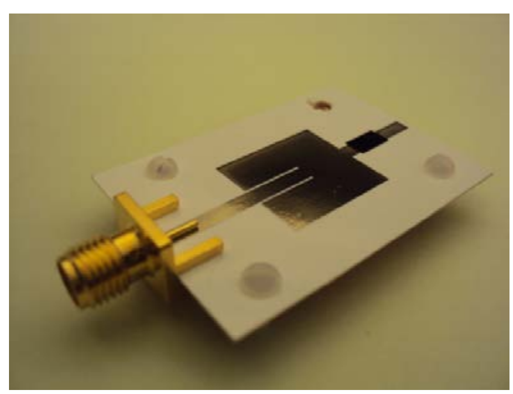

Figure 5. Fabricated prototype of inkjet-printed CNT and patch antenna on photopaper.

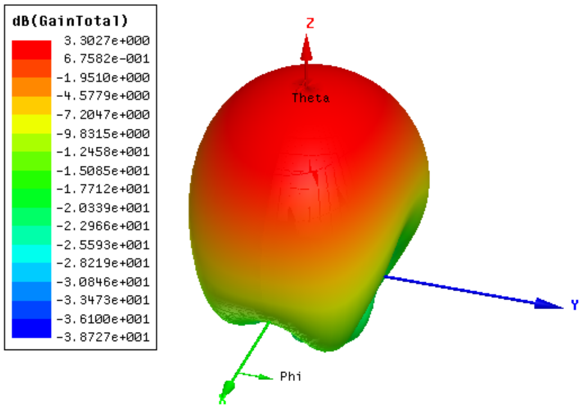

Figure 6. Radiation pattern of CNT-loaded patch antenna in CST simulation software.

Measurements showed a frequency shift of 43–49-MHz shift for ammonia concentrations ranging from 50 to 100 ppm. The change in the resonant frequency with ammonia exposure qualitatively validated the characterization model, and the sensor demonstrated both high sensitivity at low concentrations and fast return to baseline. The proposed design can be used for remote sensing and can be integrated with RFID or wireless identification and sensing platform (WISP) tags for low-cost wireless gas sensing applications.

4 WEARABLE ELECTRONICS

In this proposed design, an inkjet-printed dipole matched to a commercially available RFID chip is printed on photo paper substrate and placed above a dual split-ring resonator EBG structure also printed on photo paper substrate. Photo paper was chosen as the substrate due to its conformability and characterized electrical properties [6]. Also inkjet-printed silver traces on photo paper substrate allows for the tag to be mounted on non-flat, rugged surfaces, due to its flexible nature. Furthermore, it is an low-cost, low fabrication complexity solution for roll-to-roll mass production of tags.

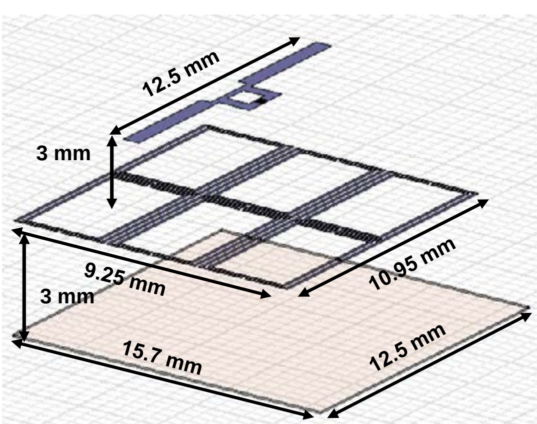

Figure 8. Dipole antenna matched to the RFID chip on top of the designed SRR-based EBG surface.

The unit cell shown in top of Fig. 7 has been simulated in CST Microwave Studio, and tuned to 915MHz with paper used as the substrate. The bottom of Fig. 7 shows the phase of reflection coefficient on the EBG structure. The reflection phase has a value between -90° and +90° in the RFID frequency band. The EBG is designed by means of reflection phase characterization [7].

Next, a dipole antenna was designed and matched to a commercially available NXP RFID SL3ICS1002 chip with a T-matching network. The impedance of the chip with an aluminum strap packaging was 13.3-j122 Ω and Fig. 8 shows the dipole antenna designed in Ansoft HFSS matched to the RFID chip (in black) over an EBG surface, which is over the paper substrate.

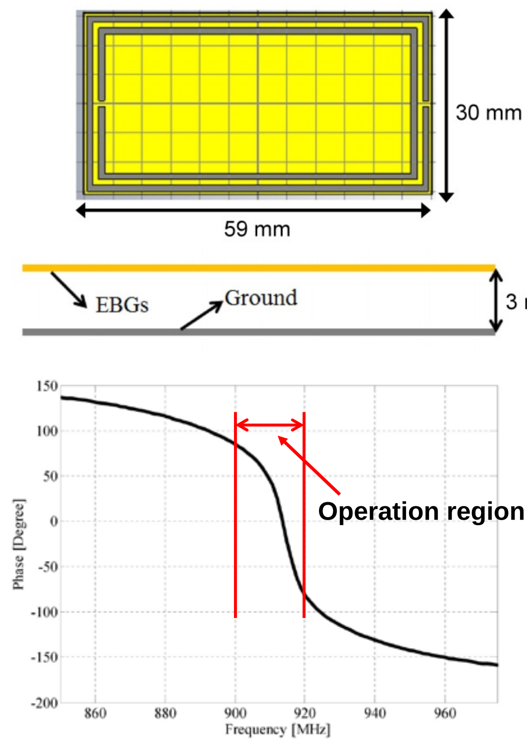

Figure 7. EBG unit cell (top) and the resulting simulated reflection phase (bottom).

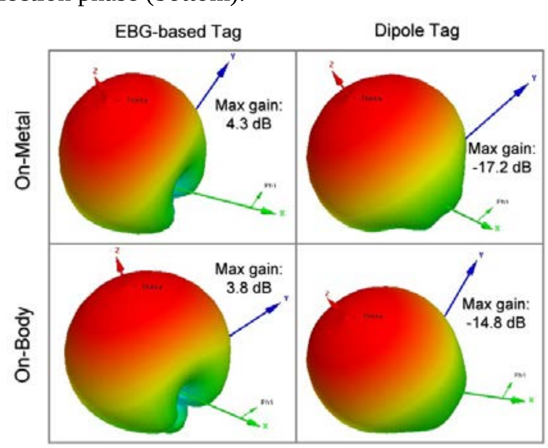

Figure 9. Simulated 3D radiation patterns of the EBG-backed and dipole Tags on both metal and body.

The simulated 3D radiation pattern of the EBG-backed shows that there is higher gain with the EBG compared to a dipole tag without the EBG. Two scenarios were simulated, as shown in Fig. 9, one with the tags on a body and one with the tags on the metal. In both cases, there was a higher gain with the EBG structure.

5 PRINTED MAGNETIC NANOMATERIAL ON INDUCTORS

A printed inductor RF module shows and demonstrates an improvement in the performance compared to previous works with inductances of up to 8 nH while maintaining a high quality factor of 25, and an SRF of 8 GHz. The inductors are integrated with printed ferromagnetic nanoparticles to investigate the high frequency performance of printed nanoparticle-based magnetic material for the first time. In this work, the RF characterization of the ferromagnetic nanomaterial for complex permittivity and permeability is first performed. The meander RF inductors are then designed and fabricated for high inductance, Q, and SRF. Measurements for the printed inductors with and without printed ferromagnetic nanomaterial are then compared with simulation.

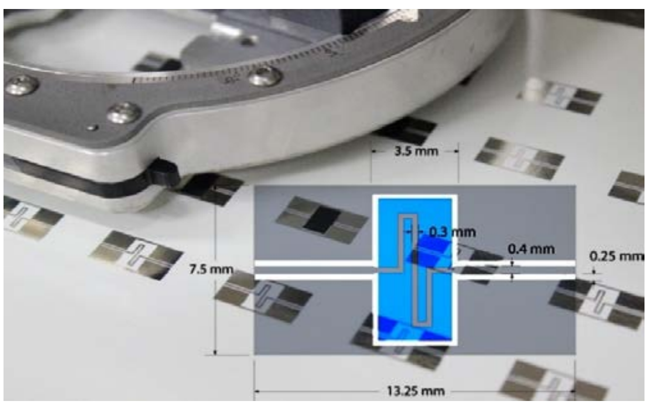

Figure 10. Inkjet printed magnetic nanomaterial on meandered inductor on photopaper.

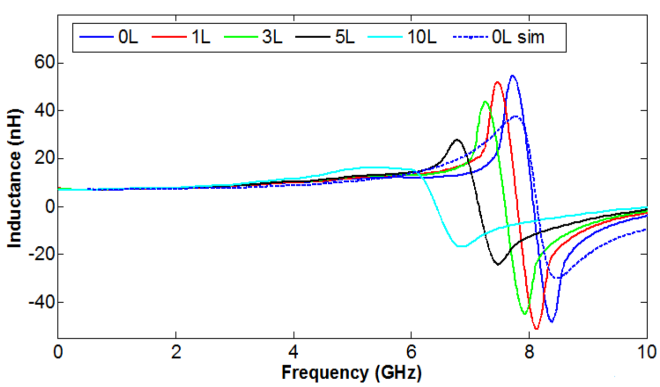

Figure 11. Measured inductance for varying number of layers of nanomaterial, showing shift in SRF.

The measured inductance of the inductor topology without the ferromagnetic nanomaterial has a value 7.5nH and SRF of 8 GHz, which matches closely with the simulation of the inductor performed in CST. For measurements that included the ferromagnetic thin film, the high permittivity of 7.3 and the permeability of 2.6 shift the self-resonance frequency down from 8 GHz to 6.44 GHz. The inductance increases from 7.15 nH to 7.35 nH at 1 GHz. The measured quality factor of the inductors show high quality factors of up to 25.

6 CONCLUSION

In this paper, several antenna and RF modules for sensing and communication applications have been introduced. The antenna-based wireless gas sensor can be utilized in several applications, given its small form factor, light weight, and little to no power requirements. There are numerous applications ranging from wearable antennas for bio-monitoring or military applications to metal-mount tags for transportation and container cargos for mass shipping. Applications for inkjet printed inductors include all-printed flexible and wearable filters, resonators, and microwave matching networks.

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