Fluidic patch antenna based on liquid metal alloy/single-wall carbon-nanotubes operating at the S-band frequency

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This letter describes the fabrication and characterization of a fluidic patch antenna operating at the S-band frequency (4 GHz). The antenna prototype is composed of a nanocomposite material made by a liquid metal alloy (eutectic gallium indium) blended with single-wall carbon-nanotube (SWNTs). The nanocomposite is then enclosed in a polymeric substrate by employing the UV-assisted direct-writing technology. The fluidic antennas specimens feature excellent performances, in perfect agreement with simulations, showing an increase in the electrical conductivity and reflection coefficient with respect to the SWNTs concentration. The effect of the SWNTs on the long-term stability of antenna’s mechanical properties is also demonstrated. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4817861]

The past decade has witnessed the rapid growth of communication and sensing applications, leading to an escalating demand for advances in antenna technologies,1–3 including mobile communications,4 compact high gain patch antennas,5 coworker14 reported an unbalanced loop antenna and a half-loop antenna.6,7 Liquid metal alloys and In 24.5%) into microfluidic channels in elastic PDMS substrates.8,9 Besides its ability to produce flexible antennas, this approach has additional advantages: (i) The process is fairly simple and scalable and can be adopted to other flexible 2D and 3D devices; (ii) it allows the antenna to be integrated with other fluidic components for tuning, sensing, and signal modulation, (iii) it does not involve etching or plating and thus does not produce hazardous waste. There are, however, challenges associated with shaping the fluid metal into more complex geometries that go beyond simple dipoles (such as the co-planar, sheet-like geometry of a patch or aperture to coupled slot antenna) due to non-uniform filling of wide microchannels. In addition, using metal liquid alone within a flexible host polymer has shown very often a poor mechanical durability.14,15

In this letter we report on the incorporation of single walled carbon nanotubes (SWNTs) within a EGaIn metal liquid alloy, yielding the fabrication of a fluidic flexible patch antenna operating at 4 GHz (S-band), thereby obtaining a radiating antenna-structure element with improved electrical properties and stable mechanical durability. Based on our simulations results, we used our developed UV-assisted direct-writing technology to design the patch antenna onto a flexible substrate, followed by injecting and encapsulating the conductive EGaIn/SWNT nanocomposites—with varying SWNTs load—that serve as a radiant antenna element material. The fluidic antennas specimen exhibited excellent performance in total agreement with our simulations. The room temperature $dc$ electrical conductivities of these antenna devices were shown to increase with respect to SWNT concentration in the nanocomposite and were about 2 orders of magnitude higher than that of the pure EGaIn, when SWNT loads range from 0.5 to 5 wt. % only. More importantly, the associated reflection coefficient has increased up to $|−101\,\text{dB}$. 

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for the same SWNT variation-range. Finally, the effect of the SWNTs on the long-term stability of the mechanical bending is also demonstrated over more than 12 months, which is a fundamental achievement towards realizing operating-stable bendable antenna devices based on SWNT and metal alloy nanocomposites.

Single wall carbon nanotubes were synthesized by using the developed plasma torch technology (detailed process can be found in Ref. 27). This process exclusively produces SWNTs that take growth in the gas-phase. The as-grown soot like SWNTs were subsequently purified by an acidic treatment through refluxing in a 3M-HNO$_3$ (Sigma Aldrich) solution.$^{28,29}$

The SWNTs were characterized by bright field transmission electron microscopy (TEM) using a Jeol JEM-2100 F FEG-TEM (200 kV) microscope. Figure 1(a) shows a representative TEM micrograph of the purified SWNT deposit, where bundles of a few SWNTs are containing individual tube diameters of about 1.2 nm. These bundles have diameters in the 2–10 nm range and lengths of the order of few tube diameters of about 1.2 nm. These bundles have diameter magnitudes. Purified SWNTs were first ultrasonicated in dimethylformamide (1 mg/ml) solution for 5 h to dissolve bundles, followed by centrifugation at 12,000 rpm for 15 min to select well-dispersed, narrow bundles of the SWNTs. The centrifuged solution was then held at 50 °C for solvent evaporation. This purification process is known to graft COOH carboxylic acid groups on the nanotube, an inherent consequence to the chemical process, which favours their dispersion.$^{28,29}$ Appropriate weights of purified SWNT were then dispersed inside a room temperature liquid EGaIn (Sigma Aldrich) using a wand-type ultrasonic processor (CP750, Cole Parmer) for 30 min. Figure 1(b) depicts the simulated geometry and dimensions of the radiating microstrip patch antenna operating at 4 GHz S-band frequency (MATLAB® solution and CST Microwave Studio® 2011 softwares were used for parameters calculations). The simulated parameters are summarised in Table I.

UV-assisted direct writing technology$^{30–32}$ was then used to design the patch antenna onto a 500 μm-thick PDMS substrate. The fabrication of the radiant antenna structure began with the deposition of an epoxy/SWNT nanocomposite filament,$^{30,33}$ under continuous UV exposure$^{30}$ leading to a solid 2-D antenna pattern (Fig. 1(c)). The shape designed by the nanocomposite filaments was then filled with the EGaIn/SWNTs nanocomposite. The final specimen was then sealed to protect the liquid nanocomposite inside the sample; a 250 μm of PDMS was gently spin-coated to encapsulate the fluidic radiant element, followed by a curing step at 85 °C for 1 h. A V-type feed connector was appropriately incorporated to measure antenna performances. Figure 1(d) shows an optical top-view image of the infiltrated patch antenna prototype.

Figure 2(a) shows the relationship between the experimentally measured electrical conductivity ($\sigma$) of the elaborated EGaIn/SWNT nanocomposites with respect to their nanotube contents (using a Hewlett-Packard 4140B semiconductor parameter analyzer). With an increase of SWNT content, the conductivity gradually increases and is about 2 orders of magnitude higher than that of pure EGaIn, when SWNT loads reach ~5 wt. % only. The stepwise change in the conductivity of the composites is a direct result of the gradual formation of an interconnected network of SWNT inside the nanocomposite. Figure 2(b) shows the reflection coefficient $S_{11}$, as a function of the frequency, for both simulation and experiment scenarios (using an Agilent 8722ES network analyzer). The experimental results show that $S_{11}$ increases from $\sim$20 dB for a pure EGaIn alloy to reach its highest value of $\sim$30 dB for a SWNT load of 5 wt. %, meaning that 99% and 99.9% of the input power is radiated from antenna, respectively. Since the pure PDMS polymer is transparent to EM radiation, the measured reflection coefficient is definitely due to the presence of the conductive material (EGaIn and SWNT). Table II summarizes the main performance parameters of the simulated and fabricated fluidic antennas as a function of the SWNTs concentration inside the nanocomposite. The average experimental uncertainty was found about ±5% over tens measured prototypes.

![FIG. 1. (a) Representative TEM images of purified SWNTs. (b) Simulated geometry and dimensions of the radiating microstrip patch antenna operating at 4 GHz S-band frequency. (c) Optical top-view image of the epoxy/SWNT-based filaments deposited by UV-assisted direct writing technology on a PDMS substrate. (d) Optical top-view image of the infiltrated patch antenna element prototype.](image-url)

**TABLE I. Simulated parameters of the radiating microstrip patch antenna operating at 4 GHz S-band frequency.**

<table>
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<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
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<td>$W_i$ (mm)</td>
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<td>$L_f$ (mm)</td>
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<td>$\sigma_{\text{SWNT}}$ (S/cm)</td>
<td>$8.5 \times 10^5$</td>
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<tr>
<td>$W_p$ (mm)</td>
<td>24</td>
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The radiation patterns of the antenna prototype were measured inside an anechoic chamber with a Hybrid Near-Field Antenna Measurement System (HNFAMS) from Antcom Corp. Simulated and measured antenna radiation patterns in the E-plane and the H-plane are shown in Fig. 2(c). The fabricated antenna exhibits somehow an omnidirectional broad beam coverage. In fact, the radiation pattern, as expected, has a main lobe for the radiation of the patch in both the 0° pattern cut. Low gain in the direction of 180° below the ground plane confirms that the patch antenna does not radiate strongly in this direction. As seen in this figure, a good agreement between simulated and measured results was obtained. In addition, it can be noted that the fluidic prototype has the same performances in terms of bandwidth and radiation pattern compared to the conventional patch antenna.

The fabricated antenna prototypes were systematically bent inside a tube of particular curvature radius. Figure 3(a) shows the variation of the reflection coefficient as a function of the curvature radius for the simulated antenna and for the specimen fabricated with SWNT loads of 0 and 5 wt.%, respectively. When the bending angle of the antenna increases, the reflection coefficient decreases accordingly, and is even below the accepted value of 1−10 dB for a curvature radius of 5 mm (recorded for the case of a pure EGaIn based prototype). At 30 mm curvature radius, all the antennas recover their initial radiation power (i.e., as that recorded before the bending). It is worth noting here that under the bending process, comparatively to the antenna specimen based on pure EGaIn (i.e., 0 wt. % of SWNT), the incorporation of 5 wt. % of nanotubes within the nanocomposite lead to a considerable improvement—up to 10 dB—of the associated reflection coefficients. This is ascribed to the enhancement of the global mechanical elasticity of the antennas brought by incorporating SWNT inside the nanocomposite. Figure 3(b) illustrates the change in the resonance frequency of the various antennas under different values of curvature. As expected, since the resonant frequency is rather related to the length of the radiant element and the effective dielectric constant of the medium, no significant change is noticed, and the antenna specimens keep a stable radiation frequency within the experimental uncertainties.

Finally, we investigated the reliability of the antenna by repeatedly bent as a function of time. Table III summarizes the long-term performances of the antennas specimen (for two different SWNT loads, namely, 0 and 2 wt. %, respectively). Even after being bent over 100 times (12 months after the first measurement under ambient conditions), the antenna specimen containing 2 wt.% only of nanotube exhibited a return losses nearly the same (within 4.3%
fluctuation) as that of the initial measurement (the effect of the whole 0.5–5 wt. % loads of SWNTs on antenna performances is in progress). On the contrary, the specimen with no SWNT content manifests a fluctuation up to 13%. No changes were noticed for the resonance frequency parameter which remains stable in both cases (with and without SWNT). Thus, the combination of a liquid metal antenna with highly electrically conductive and mechanically elastic carbon nanotube materials resulted in an antenna structure that repeatedly returns to its original shape, even after multiple deformations, without losing its electromagnetic properties.

We note that the tendency revealed by Fig. 2(b) closely suggests a possible direct correlation between the S11 of the antenna specimens and their electrical conductivity (and hence with the SWNTs-concentrations within the nanocomposite). By cross-plotting the S11 at 4 GHz of all the fabricated prototypes as a function of their associated electrical conductivities \( \sigma_{dc} \) and SWNT loads.

In summary, by using the UV assisted direct-writing technology, we demonstrated the fabrication of a fluid patch antenna based on a conductive nanocomposite material that consists of a liquid metal alloy (EGaIn) blended with SWNTs. The antennas prototypes, operating at the S-band frequency domain, have shown radiation characteristics of 90% efficiency and above (i.e., >10 dB). These antennas have displayed a resonant frequency and return losses (S11) capacity that are function of the SWNTs concentrations, in a good agreement with simulations modeling. The presented concept is promising for fluidic antennas that can be used in wireless sensing or monitoring radio systems, switches, RFID tags, conformal circuits for health monitoring, or in military and space applications.

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<td>20</td>
<td>19</td>
<td>18.5</td>
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<td>17</td>
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<tr>
<td>S11 (dB) - 2 wt. % CNT</td>
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<td>23</td>
<td>23</td>
<td>23</td>
<td>22.5</td>
<td>22</td>
</tr>
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</table>

FIG. 3. (a) Return losses (reflection coefficient, S11) at 4 GHz and (b) the resonance frequency for the simulated antenna, and these fabricated with SWNT loads of 0 and 5 wt. %, as a function of the curvature radius in mm.

FIG. 4. Reflection coefficient (S11) at 4 GHz for the whole fabricated prototypes as a function of their associated electrical conductivities \( \sigma_{dc} \) and SWNT loads.
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