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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 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 antennaÕs mechanical properties is also demonstrated.
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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 antenna,[5] or the multiple-input multiple-output (MIMO) channel technologies.[6] Although copper and other solid conductors can provide highly efficient antennas, the fatigue of copper even in the form of thin foil does not allow antennas to be continually deformed for general adaptive antenna applications. Flexible antennas have the potential to enhance the emerging field of flexible electronics.[7,8] Bendable antennas are also of interest for Ósmart antennaÓ applications such as beam-forming and beam-bending,[9] antennas for limited and nonplanar spaces,[10] and antennas for wearable health-monitoring devices, aeronautic remote sensing, or wireless strain sensors using printed radio frequency identification (RFID) tags.[3,11–13]

Flexible antennas fabricated based on polydimethylsiloxane (PDMS) and liquid metal alloys have recently been demonstrated.[14–24] For instance, Cheng *et al.*[15] and So and coworkers[14] reported an unbalanced loop antenna and a half-wave dipole antenna that were fabricated by injecting gallium indium tin (Galinstan, Ga 68.5%, In 21.5%, and Sn 10%) and eutectic gallium indium alloy (EGaIn, Ga 75.5%, and In 24.5%) into microfluidic channels in elastic PDMS substrates.

On the other hand, Kim *et al.*[25,26] recently described stretchable integrated circuits with elongation of up to 100% using wavy, thin silicon ribbons on elastic substrates. Besides its ability to produce flexible antennas, this fluidic-method 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 PDMS substrate, followed by injecting and encapsulating the conductive EGaIn/SWNT nanocomposites—with varying SWNTs loads—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 10 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 puriÞed by an acidic treatment through reßuxing in a 3M-HNO_3 (Sigma Aldrich) solution.[28,29]

The SWNTs were characterized by bright Þeld transmission electron microscopy (TEM) using a Jeol JEM-2100 FEG-TEM (200 kV) microscope. Figure 1(a) shows a representative TEM micrograph of the puriÞed SWNT deposit, where bundles of a few SWNTs are containing individual tube diameters of about 1.2 nm. These bundles have diameters in the 2Ð10 nm range and lengths of the order of few leading thereby to SWNT having an aspect ratio over three orders of magnitudes. PuriÞed SWNTs were Þrst 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 60 C for solvent evaporation. This puriÞcation 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 puriÞed 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 lm thick PDMS substrate. The fabrication of the radiant antenna structure began with the deposition of an epoxy/SWNT nanocomposite Þlament,[30,33] under continuous UV exposure[30] leading to a solid 2-D antenna pattern (Fig. 1(c)). The shape designed by the nanocomposite Þlaments was then Þlled with the EGaIn/SWNTs nanocomposite. The Þnal specimen was then sealed to protect the liquid nanocomposite inside the sample; a 250 lm of PDMS was gently spin-coated to encapsulate the ßuidic 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 inÞltrated patch antenna prototype.

Figure 2(a) shows the relationship between the experimentally measured electrical conductivity (r) 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 reßection coefÞcient 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 |20| dB for a pure EGaIn alloy to reach its highest value of |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 reßection coefÞcient is deÞnitely due to the presence of the conductive material (EGaIn and SWNT). Table II summarizes the main performance parameters of the simulated and fabricated ßuidic antennas as a function of the SWNTs concentration inside the nanocomposite. The average experimental uncertainty was found about 6 5% over tens measured prototypes.

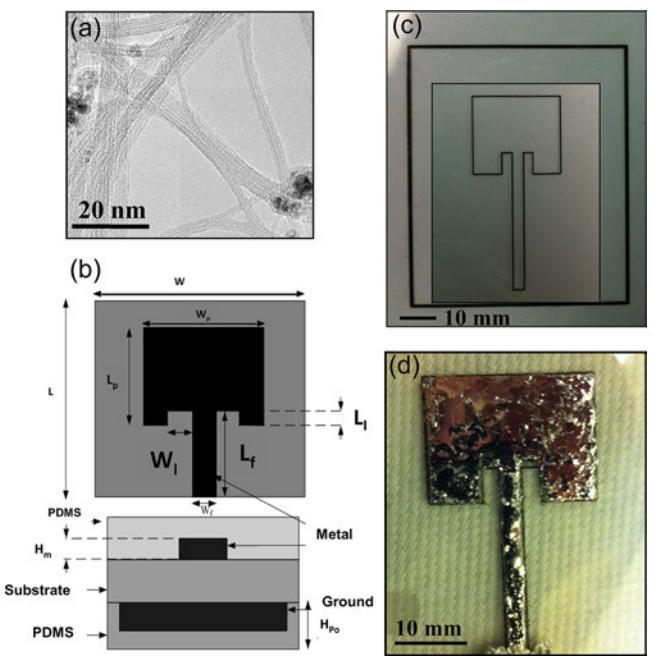

FIG. 1. (a) Representative TEM images of puriÞed SWNTs. (b) Simulated geometry and dimensions of the radiating microstrip patch antenna operating at 4 GHz S-band frequency. (c) Optical top-view image of the epoxy/SWNT-based Þlaments deposited by UV-assisted direct writing technology on a PDMS substrate.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

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

Parameters	Values	Parameters	Values
H_m (mm)	0.1	L_p (mm)	22.8
$H_{po} = h_{sub}$ (mm)	1	W_i (mm)	2.78
W (mm)	80	L_i (mm)	6.5
L (mm)	80	$e_{po} = e_{sub}$	2.5
W_f (mm)	2.78	r_{EGaIn} (S/cm)	3.4×10^4
L_f (mm)	40	r_{SWNT} (S/cm)	8.5×10^5
W_p (mm)	24		

FIG. 2. (a) Relationship between the experimentally measured electrical conductivity r_{dc} of the EGaIn/SWNT nanocomposite with respect to the nanotubes loads. (b) Reßection coefÞcient S_{11}, as a function of the frequency. (c) Corresponding simulated and experiment radiation patterns (H and E plans) at 4 GHz frequency.

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 conÞrms that the patch antenna does not radiate strongly in this direction. As seen in this Þgure, a good agreement between simulated and measured results was obtained. In addition, it can be noted that the ßuidic 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 reßection coefÞcient 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 reßection coefÞcient decreases accordingly, and is even below the accepted value of 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 reßection coefÞcients. 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,[7] no signiÞcant change is noticed, and the antenna specimens keep a stable radiation frequency within the experimental uncertainties.

TABLE II. Main antenna performance parameters (simulation and experiment) with respect to the nanotube contents into the nanocomposite.

CNT load (wt. %)	Simulations	0	0.5	1	2	3	5
Res. freq. (GHz)	4	4.03	4.02	4.01	4.01	4.02	4.02
$\|S_{11}\|$ (dB)	43	20	22	23	23	24	30
$\|FWHM\|_{GHz}$	0.2	2.16	2.08	2	1.7	1.5	1.2

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 Þrst measurement under ambient conditions), the antenna specimen containing 2 wt. % only of nanotube exhibited a return losses nearly the same (within 4.3%

FIG. 3. (a) Return losses (reßection coefÞcient) S_{11} 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.

ßuctuation) as that of the initial measurement (the effect of the whole 0.5Ð5 wt. % loads of SWNTs on antenna performances is in progress). On the contrary, the specimen with no SWNT content manifests a ßuctuation 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 S_{11} of the antenna specimens and their electrical conductivity (and hence with the SWNTs-concentrations within the nanocomposite). By cross-plotting the S_{11} at 4 GHz of all the fabricated prototypes as a function of their associated σ_{dc} values, Figure 4 conÞrms that the antenna performances of all the investigated samples increase proportionally with respect to their electrical conductivity.[34] However, despite this experimental evidence, advanced characterizations and studies are required to determine the exact inßuence of the other involved factors, such as radiant-element thickness, and the effect of other frequency domains.

FIG. 4. ReßectionCoefÞcient (S_{11}) at 4 GHz for the whole fabricated prototypes as a function of their associated electrical conductivities (σ_{dc}) and SWNT loads.

In summary, by using the UV assisted direct-writing technology, we demonstrated the fabrication of a ßuid 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% efÞciency and above (i.e., $|S_{11}| \geq 10$ dB). These antennas have displayed a resonant frequency and return losses (S_{11}) capacity that are function of the SWNTs concentrations, in a good agreement with simulations modeling. The presented concept is promising for ßuidic 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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TABLE III. Long-term antenna returns losses over storage under ambient conditions.

	Day 1	Month 1	Month 4	Month 7	Month 10	Month 12	Fluct.%
$\|S_{11}\|$ (dB) - 0 wt. % CNT	20	20	19	18.5	18	17	13%
$\|S_{11}\|$ (dB) - 2 wt. % CNT	23	23	23	23	22.5	22	4.3%

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[1]S. H. Kim, C. Jang, K. J. Kim, S. Ahn, and K. C. Choi, IEEE Trans. Electron Devices 57, 3370 (2010).
[2]J.-K. Lee, Y.-S. Lim, C.-H. Park, Y.-I. Park, C.-D. Kim, and Y.-K. Hwang, IEEE Electron Device Lett. 31, 833 (2010).
[3]S. Merilampi, T. Björninen, L. Ukkonen, P. Ruuskanen, and L. Sydänheimo, Sens. Rev. 31, 32 (2011).
[4]Y. K. Bekali and M. Essaaidi, Microwave Opt. Technol. Lett. 55, 1622 (2013).
[5]J. H. Wang, L. Sang, Z. G. Wang, R. M. Xu, and B. Yan, J. Electromagn. Waves Appl. 27, 330 (2013).
[6]E. Bjornson, P. Zetterberg, M. Bengtsson, and B. Ottersten, IEEE Commun. Lett. 17, 91 (2013).
[7]J. T. Bernhard, in Reconfigurable Antennas, Encyclopedia of RF and Microwave Engineering, edited by K. Chang (Wiley, New York, 2005).
[8]J.-C. Langer, C. Liu, and J. T. Bernhard, IEEE Microw. Wirel. Compon. Lett. 13, 120 (2003).
[9]P. S. Hall and S. J. Vetterlein, IEE Proc. 137, 293 (1990).
[10]N. Tiercelin, P. Coquet, R. Sauleau, V. Senez, and H. Fujita, J. Micromech. Microeng. 16, 2389 (2006).
[11]V. Lumelsky, M. Shur, and S. Wagner, IEEE Sens. J. 1, 41 (2001).
[12]R. H. Reuss, B. R. Chalamala, A. Moussessian, M. G. Kane, A. Kumar, D. C. Zhang, J. A. Rogers, M. Hatalis, D. Temple, G. Moddel, et al., Proc. IEEE 93, 1239 (2005).
[13]L. Gatzoulis and I. Iakovidis, IEEE Eng. Med. Biol. Mag. 26, 51 (2007).
[14]J.-H. So, J. Thelen, A. Qusba, G. J. Hayes, G. Lazzi, and M. D. Dickey, Adv. Funct. Mater. 19, 3632 (2009).
[15]S. Cheng, A. Rydberg, K. Hjort, and Z. Wu, Appl. Phys. Lett. 94, 144103 (2009).
[16]R. C. Chiechi, E. A. Weiss, M. D. Dickey, and G. M. Whitesides, Angew. Chem., Int. Ed. 47, 142 (2008).
[17]M. D. Dickey, R. C. Chiechi, R. J. Larsen, E. A. Weiss, D. A. Weitz, and G. M. Whitesides, Adv. Funct. Mater. 18, 1097 (2008).
[18]T. Sekitani, Y. Noguchi, K. Hata, T. Fukushima, T. Aida, and T. Someya, Science 321, 1468 (2008).
[19]C. Kim, Z. Wang, H.-J. Choi, Y.-G. Ha, A. Facchetti, and T. J. Marks, J. Am. Chem. Soc. 130, 6867 (2008).
[20]A. C. Siegel, S. T. Phillips, M. D. Dickey, N. Lu, Z. Suo, and G. M. Whitesides, Adv. Funct. Mater. 20, 28 (2010).
[21]L. Gatzoulis and I. Iakovidis, IEEE Eng. Med. Biol. Mag. 26, 51 (2007).
[22]B. A. Cetiner, H. Jafarkhani, J.-Y. Qian, H. J. Yoo, A. Grau, and F. De Flaviis, IEEE Commun. Mag. 42, 62 (2004).
[23]C.-P. Lin, C.-H. Chang, Y. T. Cheng, and C. F. Jou, IEEE Antennas Wireless Propag. Lett. 10, 1108 (2011).
[24]H.-J. Kim, C. Son, and B. Ziaie, Appl. Phys. Lett. 92, 011904 (2008).
[25]D.-H. Kim, J.-H. Ahn, W.-M. Choi, H.-S. Kim, T.-H. Kim, J. Song, Y. Y. Huang, L. Zhuangjian, L. Chun, and J. A. Rogers, Science 320, 507 (2008).
[26]D.-H. Kim, J. Z. Song, W. M. Choi, H. S. Kim, R. H. Kim, Z. J. Liu, Y. Y. Huang, K. C. Hwang, Y. W. Zhang, and J. A. Rogers, Proc. Natl. Acad. Sci. U.S.A. 105, 18675 (2008).
[27]O. Smiljanic, F. Larouche, X. L. Sun, J. P. Dodelet, and B. L. Stansfield, J. Nanosci. Nanotechnol. 4, 1005 (2004).
[28]B. Aõssa, L. L. Laberge, M. A. Habib, T. A. Denidni, D. Therriault, and M. A. El Khakani, J. Appl. Phys. 109, 084313 (2011).
[29]B. Aõssa, E. Hafeez, N. Tabet, M. Nedil, D. Therriault, and F. Rosei, Appl. Phys. Lett. 101, 043121 (2012).
[30]L. L. Lebel, B. Aõssa, M. A. El Khakani, and D. Therriault, Adv. Mater. 22, 592 (2010).
[31]B. Aõssa, E. Haddad, W. Jamroz, S. Hassani, R. D. Farahani, P. G. Merle, and D. Therriault, Smart Mater. Struct. 21, 105028 (2012).
[32]D. Therriault, S. R. White, and J. A. Lewis, Nature Mater. 2, 265 (2003).
[33]An Epon 828 based epoxy and SWNT nanocomposite filament of about 100 μm in thickness was first deposited onto the PDMS substrate and serve as structural walls to contain the metal fluidic alloy nanocomposite.
[34]C.-S. Zhang, Q.-Q. Ni, S.-Y. Fu, and K. Kurashiki, Compos. Sci. Technol. 67, 2973 (2007).