CubeSat Deployable Antenna Using Bistable Composite Tape-Springs

Joseph Costantine, Youssef Tawk, Christos G. Christodoulou, Jeremy Banik, and Steven Lane

***Abstract*—In this letter, a new conductive composite tape-spring is proposed for CubeSat deployable antennas that is constructed using a glass fiber reinforced epoxy with an embedded copper alloy conductor. The tape-spring is bistable enabling the antenna to be elastically stable in both the deployed and stowed states. A dipole antenna is designed, simulated, and tested to prove the viability of the electrical properties of this material.**

***Index Terms*—CubeSat, deployable antennas, space communications.**

I. Introduction

HIGH gain, circularly polarized, wideband antennas deployed on a CubeSat platform enable new communications capabilities [1]. The CubeSat is a satellite having dimensions on $10 \times 10 \times 10$ cm^3 and weighing a maximum of 1 kg [2]. So far, several antenna designs have been used and proposed for CubeSat applications. Wire antennas are a predominant choice due to their simple structure [2]–[4]. Dipoles in particular have been abundantly utilized [3], [4]. However, dipole antennas in their natural behavior do not exhibit circular polarization unless crossed together with phase shifting. Dipoles also exhibit narrow band and a relatively low gain. Arraying such dipoles in a Yagi–Uda arrangement or a log-periodic arrangement is an option that several investigators have explored [3]. Deployable helical antennas [3] are proposed as a lead candidate for CubeSat space applications due to their wide bandwidth of operation as well as their natural circular polarization behavior. Another candidate for CubeSat operation is the quadrifilar helix antenna [4]. This type of deployable antenna can be either shorted or open at the top of its conductors. This antenna structure exhibits a reasonable bandwidth. Patch antennas are also proposed as candidates [5]. Nondeployable patch antennas can be printed on one of the satellite's sides. These antennas can exhibit circular polarization and adequate bandwidth. However, their operation in a UHF band with at least 5 dB gain such as the one required for CubeSat applications requires a relatively large landscape that may not be available on a CubeSat, in addition to the fact that they naturally exhibit a low gain.

Larger satellites require other antenna types or different variations of the antennas discussed previously. The change in the satellite dimensions imposes a heavy constraint on the antenna requirements. Horn antennas are useful for applications requiring global coverage, and reflectors are popularly used in conjunction with horn feeds [6]. An example is the Harris Corporation's radial rib mesh reflector antenna that is used on NASA's Tracking and Data Relay Satellite System [7]. In addition, linearly deployed helical antennas are used on many satellites [8]. One example is the CoilAble boom supported Orbcomm Quadrifilar Helix antenna [9].

Most of the antenna types discussed above require deployment methodologies since the antennas are too large to fit inside a rocket fairing during the launch phase. A deployment method is necessary to overcome these volume constraints.

A novel composite tape-spring that is suitable for use as a structural element of deployable space structures is introduced by Murphey [10], [11]. The tape-spring has the unique property that it is neutrally stable. It is static in a continuum of positions without external forces to hold it. This class of structure is referred to as a neutrally elastic mechanism (NEM) because its behavior is functionally equivalent to typical sliding contact joint mechanisms. A consequence of this neutral stability is that diminishingly small forces are required to roll or unroll the tape-spring. According to Murphey [10], [11], such actuated NEM tape-springs offer four prominent features for deployable space structures. First, they allow controlled deployment. Second, they allow controlled retraction. Third, their neutral stability allows for zero stiffness isolators and actuators. Finally, they allow mass efficient (with respect to stiffness and strength) structures in the fully deployed configuration.

Antenna design and structural engineering are two disciplines that typically do not merge until late in the antenna design process. Initial antenna design is completed with little regard for structural requirements and constraints; at the same time, structural designs are made with little attention to their effects on antenna performance. In this letter, these two tracks are merged from the beginning to leverage structural–electrical interactions for higher antenna performance and structural efficiency.

Thomas Murphey of the Air Force Research Laboratory Space Vehicles Directorate and Adam Biskner of LoadPath, Inc., invented and developed a bistable glass composite tape-spring with an embedded conductor to be used as a deployable antenna element [12]. This structural element is the

Manuscript received January 11, 2012; revised February 16, 2012; accepted February 21, 2012. Date of publication February 29, 2012; date of current version March 26, 2012.

J. Costantine is with the Electrical Engineering Department, California State University Fullerton, Fullerton, CA 92834 USA (e-mail: jcostantine@fullerton.edu).

Y. Tawk and C. G. Christodoulou are with the Electrical and Computer Engineering Department, University of New Mexico, Albuquerque, NM 87131 USA.

J. Banik and S. Lane are with the Space Vehicles Directorate, Air Force Research Laboratory, Kirtland Air Force Base, Albuquerque, NM 87117 USA.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LAWP.2012.2189544

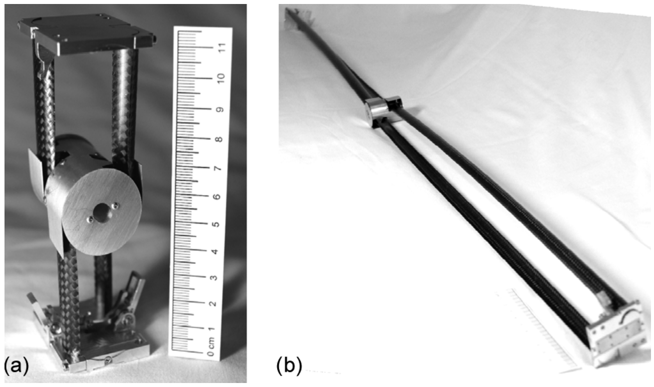


Fig. 1. SIMPLE boom shown in the (a) partially deployed and (b) fully deployed states [12], [13].

basis for the CubeSat communication antenna proposed and tested in this letter, which constitutes the first measured antenna designed with bistable composite tape-springs.

Section II of this letter details the composite tape-spring material. Section III presents the design and measurement of this tape-spring as a deployable dipole antenna. Section IV proposes a CubeSat antenna concept that could be constructed using this tape-spring material. Concluding remarks are presented in Section V.

II. Bistable Composite Tape-Spring Material

The composite tape-spring presented herein is a curved bistable composite that rolls and unrolls. The composite is stable in both its deployed and stowed states. Unlike the neutrally stable tape-spring, the bistable version has only two elastically stable physical states, fully rolled and fully extended. The intermediate state can be held stationary, but not without an external force. Therefore, physical reconfigurability (rolling and unrolling) can be accomplished with a one-way linear or rotary actuator, unlike neutrally elastic mechanism (NEM) tape-springs that require two-way actuators. A deployable structure concept that utilizes bistable tape-spring elements is presented in [12] and [13] and shown in Fig. 1.

An expanded cross section of the composite structure is shown in Fig. 2. It is composed of three plies. The top and bottom are composed of a 45° biased Astroquartz fabric impregnated with toughened epoxy. Both layers have an arc width of 0.5 in. The relative electric permittivity of these two layers is assumed to be 3.7 [14] at any frequency between 250 and 500 MHz. The relative permeability is assumed to be equal to 1, and the loss tangent is assumed to be 0.0001 [14]. The middle layer is composed of a 0.25-in-wide strip of copper alloy and epoxy filler. Astroquartz is used for its high strain to failure and low electrical conductivity characteristics. The copper alloy is used as a compromise between high strain to failure and high electrical conductivity.

III. Deployable Dipole With Bistable Composite Tape-Spring

Using the bistable composite tape-spring discussed previously, we design a dipole to operate at 250 MHz. To reduce the simulation processing time in the high frequency structure simulator by ANSYS (HFSS), the material is assumed to be of rectangular shape and not curved. We also assume the beryllium copper embedded in the middle has a width of 0.25 in. The total width of each dipole arm is 0.5 in. The total dipole length is found to be equal to 22 in, which is equivalent to 0.465λ at 250 MHz. A zoomed-in view of the curved antenna with the actual material is shown in Fig. 3. The simulated dipole with the approximated tape-spring is shown in Fig. 4 with a zoomed-in view of its excitation.

The measurement of this dipole is done by using the image method [15]. A composite tape-spring quarter-wavelength monopole approximately around 11 in long is measured on top of a large ground plane (45×60 in^2) as shown in Fig. 5.

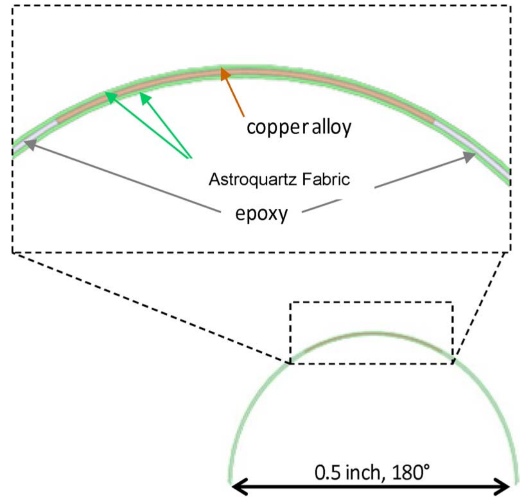


Fig. 2. Cross section of the composite tape-spring dipole with a expanded view of the central part.

Fig. 3. Dipole with the actual composite tape-spring.

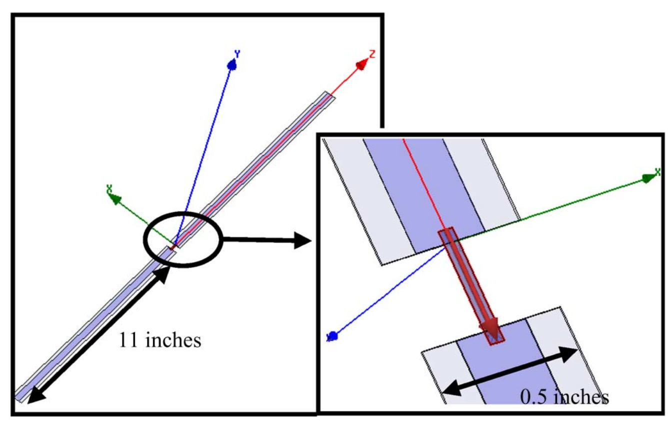


Fig. 4. Simulated dipole structure with the approximated rectangular-shaped composite tape-spring.

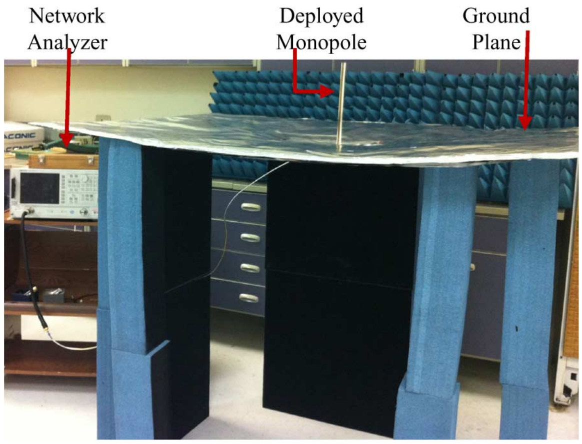
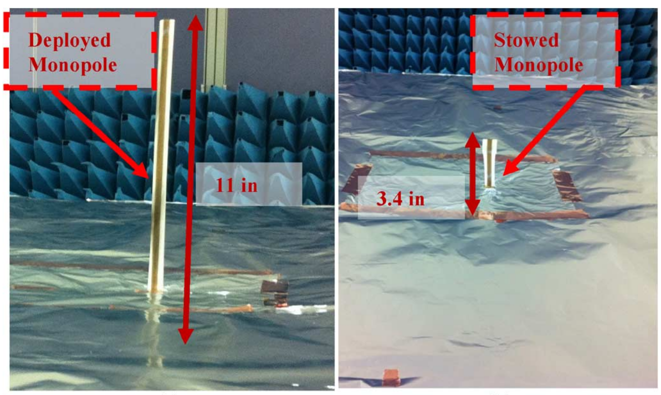


Fig. 5. Measurement setup.



(a) (b)

Fig. 6. (a) Deployed and (b) stowed monopole above the ground plane.

A photograph of the deployed (11 in) and stowed (3.4 in) monopole on top of the ground plane is shown in Fig. 6.

The antenna is rolled and unrolled about 10 times, and the reflection coefficient is measured each time with no significant changes, proving that the antenna function is preserved through mechanical cycles. The comparison between the average measured reflection coefficient and the simulated data is shown in Fig. 7. Measurement results of the monopole verify the simulation approach and the feasibility of using this composite tape-spring structure for antenna design. The simulated three-dimensional radiation pattern at 250 MHz is shown in Fig. 8.

IV. Potential CubeSat Antenna Concepts Using a Composite Tape-Spring

In the previous sections, we proved that a composite tape-spring is a successful candidate for a CubeSat deployable antenna design through simulations and measurements of a deployable dipole antenna.

Based on all the previously discussed results, we propose a log-periodic crossed-dipole array antenna designed with the bistable composite tape-spring proposed in the previous sections. With a sufficient number of elements, this antenna can achieve at least 5 dB gain and a frequency band of operation between 250 and 500 MHz. In addition to these constraints, the radiation pattern of the proposed antenna is directive away from

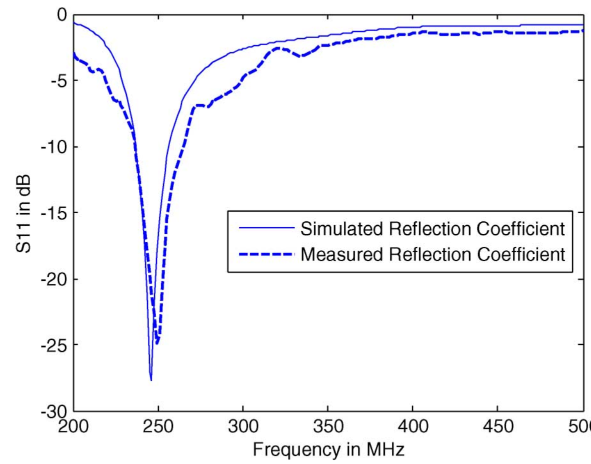


Fig. 7. Comparison between the monopole's measured reflection coefficient and the dipole's simulated reflection coefficient showing great analogy.

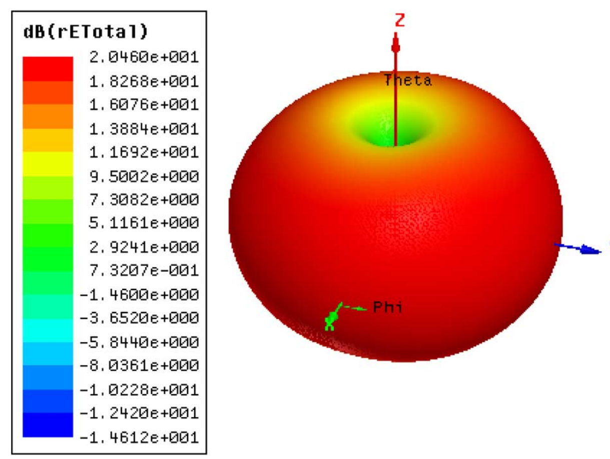


Fig. 8. Dipole antenna's 3-D radiation pattern at 250 MHz.

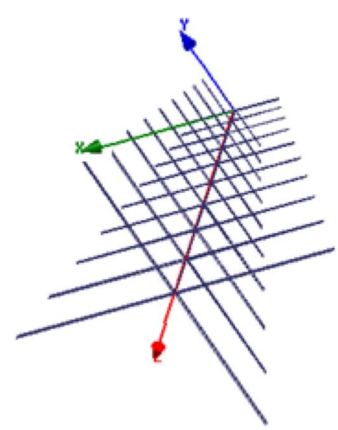


Fig. 9. Proposed composite tape-spring log-periodic crossed-dipole antenna array concept.

the small element where the directivity of this array antenna is determined by the log periodicity of the elements [15]. This antenna concept is shown in Fig. 9.

To confirm the validity of the log-periodic design as a good candidate for CubeSat, we simulate a three-element log-periodic dipole antenna array that is shown in Fig. 10. This antenna operates between 380 and 500 MHz as shown in Fig. 11. The three

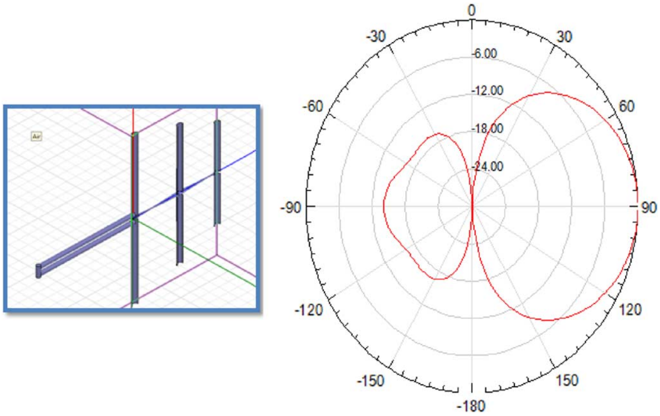


Fig. 10. Three-element copper-based log-periodic antenna array with its radiation pattern at 540 MHz at the E-plane cut.

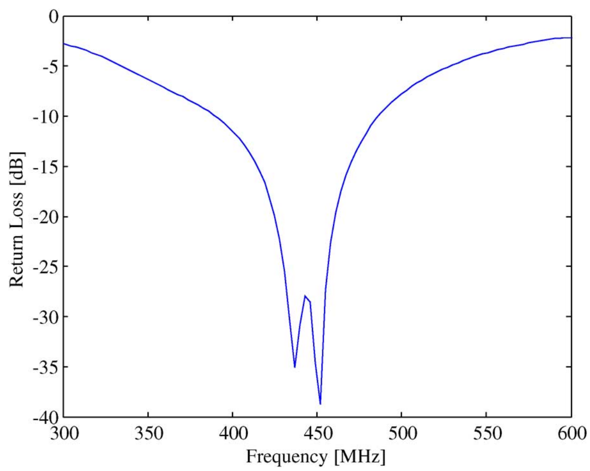


Fig. 11. Reflection coefficient of the three-element log-periodic antenna.

elements have lengths of 8.05, 6.5, and 4.78 in, respectively. The radiation pattern of this antenna array shown in Fig. 10 is directed away from the small element. This is the first step in completing the proposed crossed-dipole log-periodic array. Crossing the elements for circular polarization and increasing their number to improve the bandwidth as well as measuring the full deployable prototype constitute our next step. All the results shown in Figs. 10 and 11 confirm that this deployable antenna concept is valid for CubeSat applications.

V. Conclusion

In this letter, a bistable composite tape-spring is proposed to be used as an antenna element. This element is used in a deployable dipole antenna concept. The material is bistable, allowing the antenna to be structurally stable in both the rolled and unrolled states. The composite tape-spring dipole antenna is designed, simulated, and measured to show fidelity of the modeling approach and feasibility as a functional antenna. The measurement of this dipole is achieved using a quarter-wavelength tape-spring monopole and image method.

A deployable log-periodic crossed-dipole antenna concept is proposed as a potential candidate for CubeSat applications. Its radiation pattern characteristics and its gain and bandwidth prospects confirm its validity for CubeSat.

In this letter, we prove that the use of the proposed composite tape-spring is valid for deployable antenna design. Designing antennas with this tape-spring constitutes the first step in merging structural engineering with antenna design concepts. This merging introduces new deployable antenna possibilities. The designs based on such composites are proven to be robust, rigid, and stable to satisfy all the constraints of a CubeSat platform.

References

[1] H. Heidt, J. Puig-Sauri, A. Moore, S. Nakasuka, and R. Twiggs, "CubeSat: A new generation of Picosatellite for education and industry low-cost space experimentation," in *Proc. 14th Annu. AIAA/USU Conf. Small Satell.*, Logan, UT, Aug. 2000, SSC00-V-5.

[2] H. J. Yousuf, M. M. Haider, M. K. Siddique, and M. Amin, "Analysis of G-shape antennas mounted on a CUBESAT," in *Proc. 2nd Int. Conf. Adv. Space Technol.*, Islamabad, Pakistan, Nov. 2008, vol. 2, pp. 28–32.

[3] P. Muri, C. Obulpathi, and J. McNair, "Enhancing small satellite communication through effective antenna system design," in *Proc. 2010 Mil. Commun. Conf., Unclassified Program*, San Jose, CA, Nov. 2010, pp. 347–352.

[4] S. Gao, K. Clark, M. Unwin, J. Zackrisson, W. A. Shiroma, J. M. Akagi, K. Maynard, P. Garner, L. Boccia, G. Amendola, G. Massa, C. Underwood, M. Brenchley, M. Pointer, and M. N. Sweeting, "Antennas for modern small satellites," *IEEE Antennas Propag. Mag.*, vol. 51, no. 4, pp. 40–56, Aug. 2009.

[5] C. G. Kakoyiannis and P. Constantinou, "A compact microstrip antenna with tapered peripheral slits for CubeSat RF payloads at 436 MHz: Miniaturization techniques, design & numerical results," in *Proc. IEEE IWSSC*, Toulouse, France, Oct. 2008, pp. 255–259.

[6] T. Kitsuregawa, *Advanced Technology in Satellite Communication Antennas*. Norwood, MA: Artech House, 1990, p. 299.

[7] Y. Rahmat-Samii, A. Zaghloul, and A. Williams, "Large deployable antennas for satellite communications," in *Proc. Antennas Propag. Soc. Int. Symp.*, Salt Lake City, UT, Jul. 2000, vol. 2, pp. 528–529.

[8] J. Kraus, *Antennas*, 2nd ed. New York: McGraw-Hill, 1988, pp. 270–271, 703–709.

[9] ATK, "Coilable boom systems," Data sheet, Accessed Sep. 29, 2011 [Online]. Available: http://www.atk.com/Products/documents/Coilable%202011.pdf

[10] T. W. Murphey and S. Pellegrino, "A novel actuated composite tape-spring for deployable structures," AIAA, Reston, VA, Tech. Rep. TR-1528, Apr. 2004.

[11] T. W. Murphey, S. Jeon, A. Biskner, and G. Sanford, "Deployable booms and antennas using Bi-stable tape-springs," in *Proc. 24th AIAA/USU Conf. Small Satell.*, Logan, Utah, SSC10-X-6.2010.

[12] T. W. Murphey, S. Jeon, A. Biskner, and G. Sanford, "Deployable booms and antennas using bi-stable tape-springs," in *Proc. 24th AIAA/USU Conf. Small Satell.*, Logan, Utah, SSC10-X-6.

[13] S. Jeon and T. W. Murphey, "Design and analysis of a meter-class CubeSat boom with a motor-less deployment by bi-stable tape springs," in *Proc. 52nd AIAA Struct., Struct. Dynam., Mater. Conf.*, Palm Springs, CA, Apr. 4–7, 2011, AIAA-2011-1731.

[14] JPS Composite Materials, "JPS Composite Materials," 2011 [Online]. Available: http://jpsglass.com/

[15] C. A. Balanis, *Antenna Theory Analysis and Design*, 3rd ed. Hoboken, NJ: Wiley, 2005.