Design and Implementation of a Diplexer and a Dual-Band VHF/UHF Antenna for Nanosatellites

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***Abstract*—CONSAT1 is a nanosatellite of the form 3U CubeSat designed and built by the Space Concordia group at Concordia University during the first Canadian Satellite Design Challenge (CSDC). Its mission is to detect and study high-energy particles in low earth orbits. This CubeSat relies on a single antenna to communicate with a ground station. The antenna feeds a diplexer that separates the transmit and receive frequencies. This letter shows the design and implementation of a dual-band spring-steel monopole antenna that resonates at both the uplink frequency of 146 MHz and the downlink at 438 MHz, and the associated diplexer. Agreement between simulation and pre-launch measurement on the flight hardware is demonstrated.**

***Index Terms*—Bandpass filter, CubeSat, diplexer, low earth orbit (LEO), nanosatellite, satellite antennas, satellite communications, small satellites.**

I. Introduction

IN RECENT years, there has been an increasing interest in nanosatellites for space research. Because of low manufacturing and launch costs, nanosatellites are inexpensive platforms for scientific payloads and for testing new technology [1], [2]. They provide university researchers with easy access to space, and students with hands-on educational projects [3], [4].

Concordia's satellite, called ConSat1, has a mission to detect and study high-energy particles in a low Earth orbit (LEO). Important considerations include the size restrictions of the CubeSat, the attitude control system employed in the mission, the overall power available for the communication subsystem, and the surface area that will be allocated to solar panels, the payload, and the antenna. The satellite will fly in low Earth orbit and be visible to the ground station in a short "communications window" in each orbit.

When high-speed transmission is required for the downlink of payload data such as images, CubeSats usually contain a set of low-gain antennas for telemetry, tracking, and command; and a high-gain antenna for transmitting the payload data [1], [5], [6]. Reference [5] lists some of the simple and inexpensive antennas

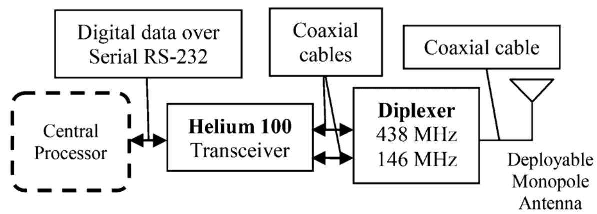

Fig. 1. Block diagram of the communication system.

that have been used in modern small satellites: monopole antennas, printed inverted-F-shaped antennas, patch antennas, and helical antennas.

Muri *et al.* [1] compared the performance of a small dipole, a large dipole, a patch, and a commercial and a prototype helical antenna in terms of received signal strength indication (RSSI), taking into account factors such as frequency capabilities, complexity, and feasibility, but mainly gain and size, and concluded that the patch antenna outperformed the others. However, the helical antenna is also a good candidate due to its high gain and better efficiency [1]. Gao *et al.* [5] stated that besides being lightweight, providing broad coverage, and presenting low cross polarization, a quadrifilar-helix antenna has the advantage that it is possible to shape its radiation pattern to obtain the desired coverage. Helical antennas are usually larger than patch antennas [6].

Kakoyiannis and Constantinou [7] designed a circularly polarized patch antenna that operates at 434.8–438 MHz using miniaturization techniques. The authors discuss the challenges in designing patch antennas at UHF given the size restrictions of CubeSats, emphasizing the fact that electrically small antenna performance suffers, and suggesting the use of patch antennas at higher frequencies such as 2.4 GHz.

The Consat1 communication subsystem consists of a radio transceiver, a diplexer, and an antenna, as shown in Fig. 1. The transceiver chosen was the AstroDev He-100 radio because of its compatibility with standard amateur ground stations, which are capable of communicating at bit rates of 1200 and 9600 b/s or higher depending on the modulation scheme. The radio supports the AX.25 packet protocol [8]. It is a full-duplex radio that transmits at 420–450 MHz and receives at 120–150 MHz, both amateur frequency bands. Atmospheric attenuation is lower than 1 dB at both frequencies [2]. Simultaneous uplink and downlink transmission is advantageous due to the short communication window of a satellite in LEO. The transceiver consumes 3 W of power. The output power at the transmit port is slightly greater than 1 W.

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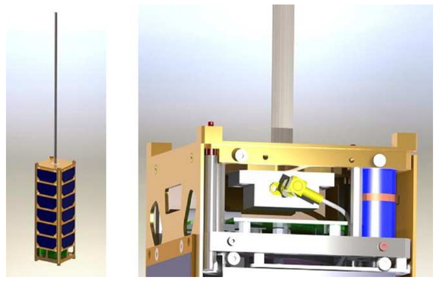

Fig. 2. CubeSat model.

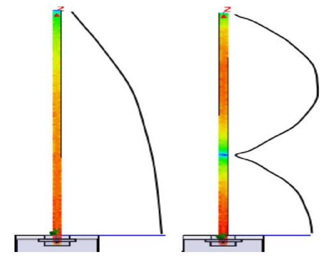

Fig. 3. Current density on the antenna element. Current density at *(left)* 146 MHz and *(right)* 438 MHz.

The attitude control for ConSat1 uses a magnet-based passive control system to align the z-axis of the CubeSat with Earth's magnetic field, with no xy position control. Hence, an antenna aligned with the z-axis that is omnidirectional in the xy-plane is a suitable choice. Since most of the surface area of the CubeSat is covered with solar panels, the antenna is to be mounted on the end of the satellite. A monopole antenna is a suitable choice, shown in Fig. 2. The mechanical deployment of the antenna is one of the most challenging problems of the whole mission.

The antenna itself is a length of spring steel. During launch, it is bent 180° so that most of the length of the antenna lies parallel to the satellite body. The tip of the antenna is attached to the body by a nylon wire connected to a nichrome wire, which heats up after the satellite is ejected from the launching vehicle, burning the nylon wire. Then, the spring-steel strip straightens itself and the antenna is deployed.

Fig. 1 is a block diagram of the communication system. It uses a diplexer to separate the transmit (Tx) and receive (Rx) frequencies of 438 and 146 MHz, respectively. The diplexer comprises two bandpass filters, one from the radio to the antenna at the transmit frequency and the other from the antenna to the radio at the receive frequency. This allows the communication subsystem to use a single antenna to both transmit and receive data simultaneously. Using a single antenna simplifies the CubeSat's design and helps meet the CubeSat's size and weight restrictions.

This letter discusses the design and construction of a spring-steel dual-band monopole antenna and the associated diplexer for the Consat1 CubeSat.

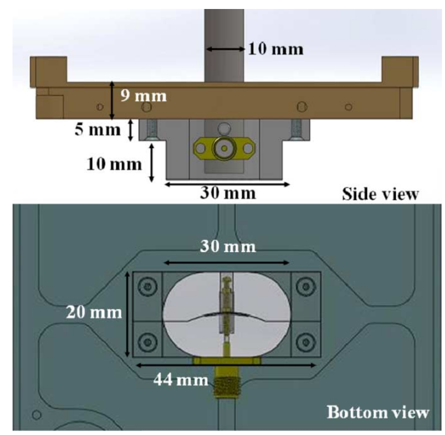

Fig. 4. *(top)* Side view and *(bottom)* bottom view of the antenna mount. The gray strip represents the spring-steel antenna element that is 54.5 cm long, 1 cm wide, and 0.15 mm thick. The light-gray region represents Teflon material. The two holes above the feed point on the antenna element that have Teflon rods through them keep the antenna element aligned.

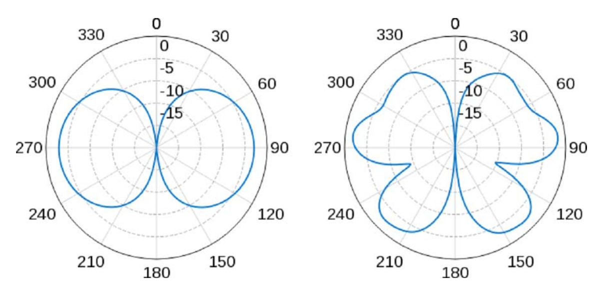

Fig. 5. Radiation patterns of the antenna at *(left)* 146 MHz and *(right)* 438 MHz.

II. Antenna

The downlink frequency of 438 MHz and the uplink frequency of 146 MHz have a 3:1 ratio, which allows a monopole antenna to be resonant at both frequencies. Fig. 3 shows that the current density magnitude on the antenna element at 146 MHz is a $\lambda/4$ standing wave, and at 438 MHz is a $3\lambda/4$ standing wave. These choices allow the antenna to provide a good impedance match to a 50-Ω transmission line at both frequencies.

The antenna consists of a strip of spring steel clamped at its base in a Teflon holder as shown in Figs. 2 and 4. The antenna was designed with the High Frequency Structural Simulator (HFSS) [9] tool. The first step in the design process was to vary the length of the antenna itself to obtain satisfactory radiation patterns for the antenna mounted on the CubeSat body. The radiation patterns are omnidirectional in the xy-plane perpendicular to the monopole. The patterns are shown in the yz-plane in Fig. 5. At the receive frequency of 146 MHz, the pattern is very close to that of a half-wave dipole antenna. The gain is 2.06 dB, and the half-power beamwidth (HPBW) is 79.5°. At the transmit frequency of 438 MHz, the pattern has a minimum of -10.3 dB at 112°, which is acceptable in the sense that the antenna radiates over a wide range of angles centered at 90°. The gain at 84° is 3.35 dB, and the HPBW is 27.5°. Note that the antenna must never point toward the ground station due to the presence of a null on the z-axis in the radiation pattern.

At the best choice for length, the input impedances of the antenna at 146 and 438 MHz were not close enough to the desired 50 Ω. This required an antenna mount that would provide both solid mechanical support and impedance matching. The antenna mount is made of Teflon with relative permittivity 2.1 and is enclosed in a metal cavity, as shown in Fig. 4. The dimensions of

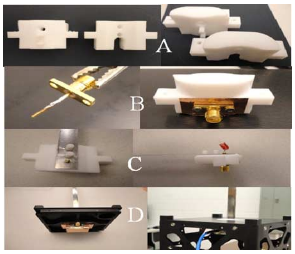

Fig. 6. (A) Teflon clamp parts. (B) SMA connector with brass screw extending the center conductor, and Teflon holder. (C) Antenna element attached to the Teflon mount. (D) Antenna assembly.

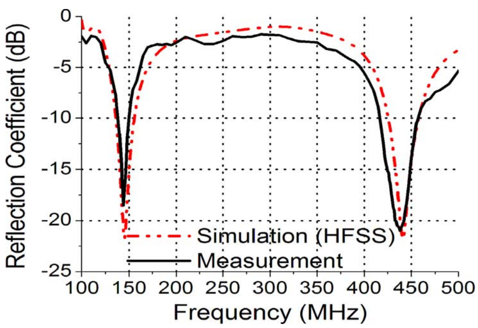

Fig. 7. Comparison between measured and simulated reflection coefficient of the antenna.

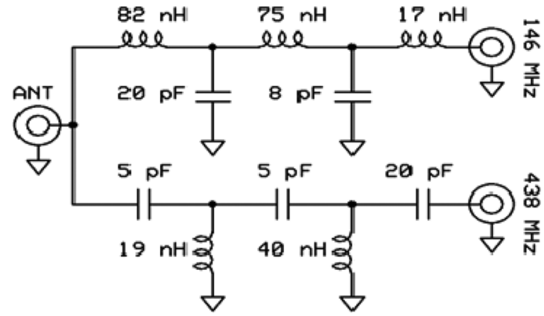

Fig. 8. Circuit schematic of the diplexer.

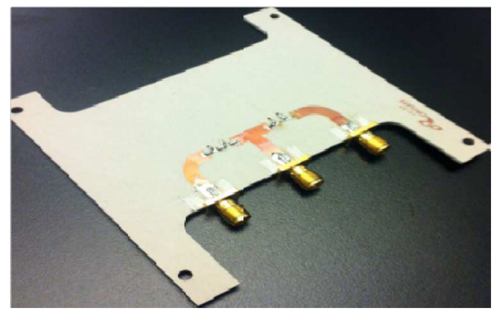

Fig. 9. Diplexer. The port at left is the Tx port, the port at right is the Rx port, and the port in the middle is the antenna port.

the cavity and the Teflon pieces were chosen using HFSS analysis to obtain a good impedance match to the 50-Ω line at the SMA connector feeding the antenna.

Fig. 6 illustrates the assembly stages for the antenna mount. The spring-steel antenna element is squeezed tightly between two Teflon pieces that allows the spring-steel strip to keep its natural curvature (Fig. 6, parts A and C). This helps the antenna element to be straight after its deployment. The feed for the antenna uses a brass screw soldered to the center pin of the SMA connector, B in Fig. 6, which extends through the antenna strip, and is held tightly against the strip by a nut. It is not possible to solder to the steel strip, and so the screw and nut provide reliable electrical contact. To provide mechanical support for the antenna, there are two holes in the strip above the feed point, C in Fig. 6, which allow Teflon rods to go through the strip to keep the antenna element aligned. A small coil is connected between the antenna feed point and the satellite body to provide a low-impedance path for static charge accumulation on the antenna element to discharge, but provide a high impedance at both the transmit and receive frequencies.

Fig. 7 compares the simulated and measured reflection coefficient of the antenna in the mount of Fig. 6. The antenna mount, antenna, and satellite were modeled with HFSS to compute the reflection coefficient. The distance of the feed point from the end of the antenna strip is a critical parameter in obtaining a good impedance match. The reflection coefficient of the antenna is below -20 dB at both the operating frequencies. Hence, the input impedance of the antenna and its feed is close to 50 Ω.

III. Diplexer

A diplexer is a passive three-port device that allows signals at two different frequencies to share a common communication channel. Fig. 8 shows the diplexer's circuit schematic. The diplexer consists of two bandpass filters. One filter is designed to allow the 146-MHz signal to pass while having a high input impedance at 438 MHz to separate the receive (Rx) frequency from the transmit (Tx). The other passes the 438-MHz signal, but presents a high impedance at 146 MHz. The high-power Tx signal from the transceiver passes through the 438-MHz filter to the antenna port, but is blocked by the 146-MHz filter from reaching the Rx port. On the other hand, the 146-MHz signal received by the antenna goes through the 146-MHz filter of the diplexer to the transceiver's Rx port. Because the uplink and downlink frequencies are so different, the diplexer can provide good isolation, allowing simultaneous transmission and reception.

Fig. 9 shows the diplexer board. The laminated substrate used was RT/Duroid 6002 from Rogers Corporation. This laminate was chosen because it has low outgassing, extremely low thermal expansion coefficient, and well-known dielectric constant of 2.94. It is ideal for space applications [10]. Knowing the dielectric constant of the substrate and its thickness allows the width of the microstrip lines to be designed for a characteristic impedance of 50 Ω. The ports on the left and right in Fig. 9 are connected to the transmit and receive ports of the transceiver, respectively, by 50-Ω coaxial cables; the center port of the diplexer is connected to the antenna by a 50-Ω cable. The design of the diplexer was verified and optimized by using the Advanced Design System (ADS) [11].

Fig. 10 compares the simulated and measured performance of the diplexer. The reflection coefficient shows a frequency shift of about 20 MHz between the measured and simulated curves. At 438 MHz, the measured curve has a reflection coefficient of -22.7 dB ($\Gamma = 0.0733$), which means that only 0.54% of the

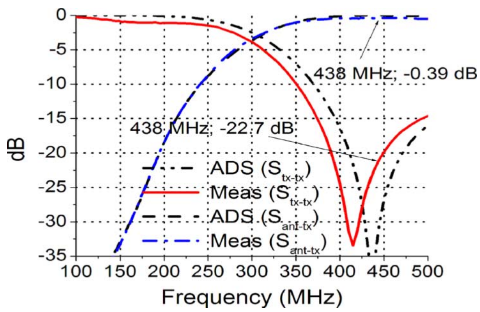

Fig. 10. Reflection coefficient at the Tx port of the diplexer and transmission coefficient from the Tx port to the antenna port of the diplexer.

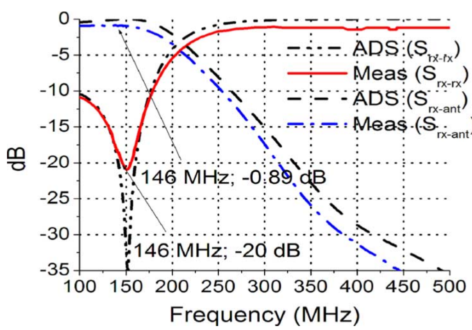

Fig. 11. Reflection coefficient at the Rx port of the diplexer and transmission coefficient from the antenna port to the Rx port of the diplexer.

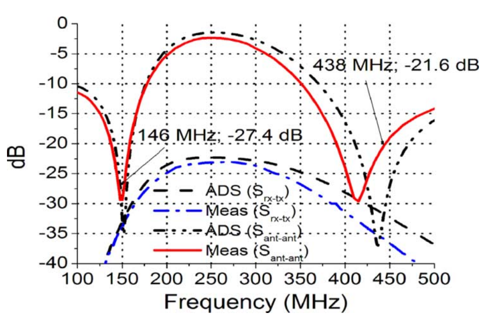

Fig. 12. Reflection coefficient at the antenna port of the diplexer.

power transmitted is reflected back into the Tx port of the transceiver, for a standing-wave ratio (SWR) of 1.15. Fig. 10 shows the transmission coefficient from the Tx port of the diplexer to the antenna port. There is an insertion loss of 0.39 dB at 438 MHz, which corresponds to a transmission coefficient of 0.956, and a power loss of 8.6%.

Fig. 11 shows both the reflection coefficient at the Rx port of the diplexer and the transmission coefficient from the antenna port to the Rx port. The 438-MHz signal is rejected by the filter, but the 146-MHz signal is passed with an insertion loss of 0.89 dB, for a transmission coefficient of 0.903 and a power loss of 18.5%. The simulation and measurement are in reasonable agreement.

Fig. 12 shows the reflection coefficient at the antenna port of the diplexer. The reflection coefficient is lower than −20 dB at both 146 and 438 MHz, which was expected since this port was designed to have an impedance of 50 Ω at both frequencies. Fig. 12 also shows the transmission coefficient from the Tx port to the Rx port of the diplexer, which at 438 MHz is −35.5 dB ($T = 0.017$). Thus, only 0.028% of the transmitted power reaches the Rx port transceiver. This is crucial for protection purposes since high power at the Rx port can destroy the front end of the transceiver. Also, since most of the power delivered by the Tx port of the transceiver is radiated by the antenna, the limited power generated by the CubeSat is used efficiently.

IV. Conclusion

This letter described the design and implementation of a dual-band spring-steel monopole antenna that resonates at 438 and 146 MHz, the feed arrangement for the antenna, and the design of a diplexer for use in a nano-class satellite known as a 3U CubeSats. This antenna and this diplexer together form an essential part of the nanosatellite's communication system.

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