Active Antennas for CubeSat Applications

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***Abstract*—An active antenna known as a grid oscillator is presented for use onboard the University of Hawaii's CubeSat. It operates at high frequencies that will be able to facilitate future, more data-intensive missions. The device uses an efficient power-combining scheme packaged in a compact, low-profile structure that can be mounted on the side of a cube. The active antenna consists of an array of transistors directly embedded into a planar radiating structure. An infinite-array approximation is used to simulate the grid design in CAD programs. Various mounting schematics are presented for the grid oscillator that is currently being fabricated with a desired oscillation frequency of 5.85 GHz.**

I. Introduction

Recently, Professor Robert Twiggs of Stanford University's Space Systems Development Laboratory conceived a program known as CubeSat, with the intention of exposing students to the various aspects of small-satellite design, manufacture, and operation within a span of approximately one year. [1] Design constraints include a mass no greater than 1 kg and a maximum volume of 1000 cm^3. The University of Hawaii's CubeSat program, now in its first year, is unique in that it is composed almost entirely of undergraduates. It is the largest project ever undertaken by a multidisciplinary group of engineering students in the university's history, with over 50 students and nine faculty advisors.

CubeSat communication systems at practically every university currently operate in the UHF/VHF range. While this frequency range is sufficient for current CubeSat missions, future data-intensive missions – such as the imaging of the Moon – will require communication at a higher frequency to provide greater data-transmission rates. However, high-frequency communication presents a number of challenges. Higher frequencies require a larger transmit power due to the greater link loss, making it necessary to use higher power semiconductor devices. Unfortunately, the RF output power available from semiconductor devices drops off with a 1/f to 1/f^2 frequency dependence (as shown in Fig. 1), making it necessary to employ some form of power-combining scheme to provide adequate transmit power. Although a variety of power combiners based on conventional circuit techniques have been developed, they occupy large amounts of area and are inefficient for large numbers of devices, making them impractical for use in a CubeSat.

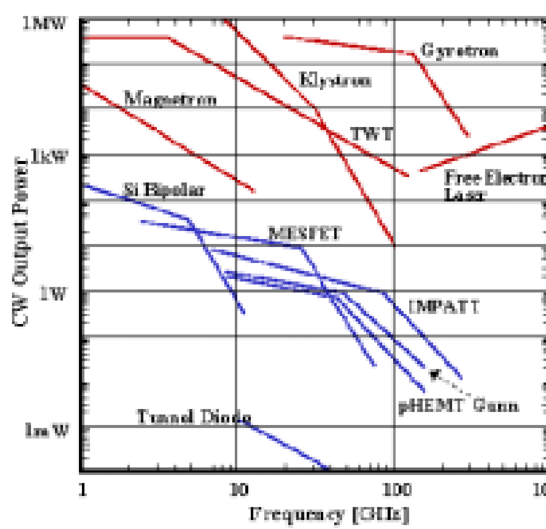


Fig. 1: Output power versus frequency for vacuum and solid-state devices.

We present an active antenna for the University of Hawaii's CubeSat that allows high-frequency operation and an efficient power-combining scheme, all packaged in a compact, low-profile structure that can be mounted on the side of a cube. The University of Hawaii's active antenna will be the first of its kind in space, and will help lay the groundwork for future, more data-intensive CubeSat missions.

This paper is organized as follows: the principle of operation of the active antenna is presented in Section II, followed by discussion of its design in Section III, then experimental results in Section IV, and finally mounting of the antenna onto the cube in Section V.

II. Grid Oscillators

The active antenna being developed by the University of Hawaii CubeSat team is known as a grid oscillator. [2, 3] A grid oscillator is shown schematically in Fig. 2, where a metal grating is loaded with an array of active devices. The metal grid, which serves as a DC-bias distribution circuit, RF-embedding circuit, and radiating structure, is printed on a dielectric substrate backed by a metal mirror that provides the feedback necessary for oscillation. The vertical leads of the grating serve as antennas, and the horizontal leads as DC bias lines. If properly designed, the bias lines do not affect the high-frequency performance of the active grid, as the radiated electric field is vertically polarized.

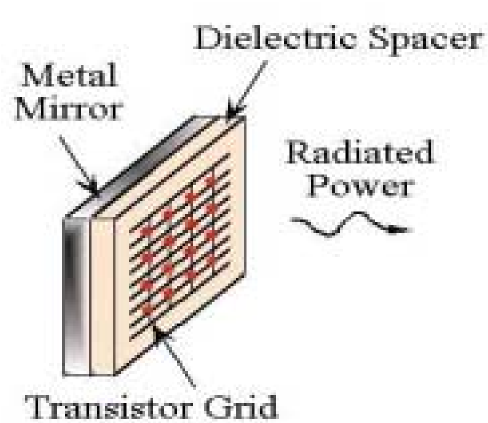


Fig. 2: Schematic of a grid oscillator.

When DC bias is applied, oscillation is triggered by transients or noise, and each device oscillates at a different frequency. A noncoherent wave radiates from the grid, reflects off the mirror, and injection locks the oscillating devices. At the onset of oscillation, different modes of the cavity compete, as in a laser. The mode with the lowest diffraction loss most likely dominates. After a few round trips, the higher-order modes lose most of their power to diffraction, resulting in a single-frequency, self-locked, coherent oscillation. [3] The output power from each device is combined in free space, making this power-combining scheme quite efficient.

Conventional CubeSats use wire or strip antennas, which must be deployed and require additional circuitry. A grid oscillator is a low-profile, planar structure requiring no deployment, with the electronics already embedded within the structure. Unlike typical phased-array antennas, the spacing between devices is only on the order of a tenth of a free-space wavelength, making it very compact at microwave frequencies. Also, because of its built-in redundancy, a grid oscillator is tolerant to single-point failures, which minimizes the probability of failure of the entire component.

III. Design

Due to the complicated electromagnetic field interactions between the active devices, metal grating, and dielectric substrate, modeling of the grid can be very difficult. [4] To address these problems, edge effects are ignored by assuming that the grid is infinite in extent, as shown in Fig. 3.

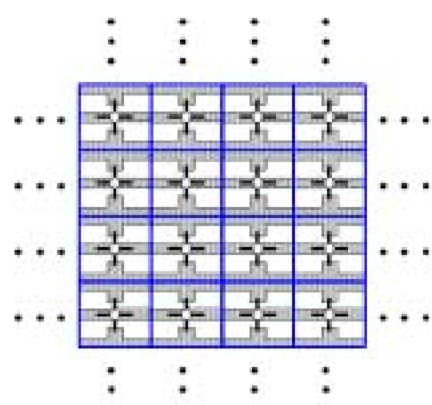
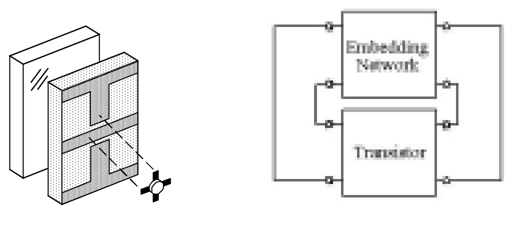


Fig. 3: An infinite-array approximation creating symmetrical boundary conditions.

This infinite-array approximation provides planes of symmetry that allows characterization of the entire grid with the unit cell, shown in Fig. 4(a).

The unit cell can be separated into two parts: a passive part (consisting of the substrate, metal grid, mirror, and free space), and an active part (consisting of the transistor). The passive part is characterized using full-wave electromagnetic techniques which results in a two-port scattering-parameter network. [5] The active part is characterized with the transistor scattering parameters. The result is shown in Fig. 4(b), in which the interconnection of the passive and active networks forms a closed loop.



(a) (b)

Fig. 4: (a) Unit cell with transistor and grid separated, and (b) unit cell separated into an embedding network and the transistor.

Microwave Office, a commercially available computer-aided microwave circuit simulator, is used to simulate the loop gain of this equivalent circuit. The oscillation frequency is indicated when the loop gain has a magnitude greater than one and a 0^{o} phase shift, as shown in Fig. 5.

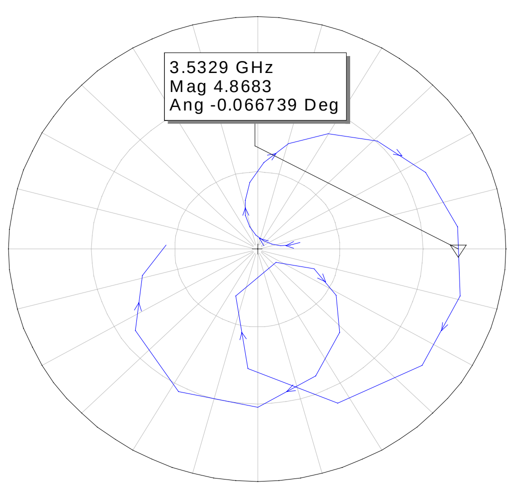


Fig. 5: Simulated loop gain for a grid oscillator. Oscillation is achieved at 3.53 GHz.

IV. Experimental Results

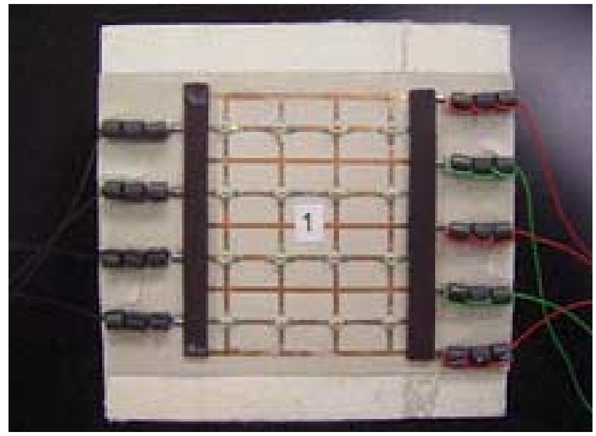


Fig. 6: A 4.1-GHz grid oscillator designed by former University of Hawaii undergraduate electrical engineering students. [6] This design uses a 10x12 mm unit cell with ferrite beads to isolate dc biasing.

Shown in Fig. 6 is a grid oscillator that was fabricated at the University of Hawaii. [6] This 4x4 grid was printed on a 0.254-mm-thick Rogers *Duroid* substrate with $\varepsilon_r = 10.2$. The active devices are Agilent ATF-36077 pseudomorphic high-electron mobility transistors. The optimum-operating configuration for this grid consisted of a 12.7-mm-thick layer of *Eccostock* HiK ($\varepsilon_r = 10.2$) inserted between the substrate and the mirror. The grid was biased at $V_{DS} = 1.7$ V, $I_{DS} = 71.4$ mA, $V_{GS} = -0.495$ V, and operated at 4.12 GHz with an effective isotropic radiated power of 63.5 mW. The radiation pattern is shown below in Fig. 7.

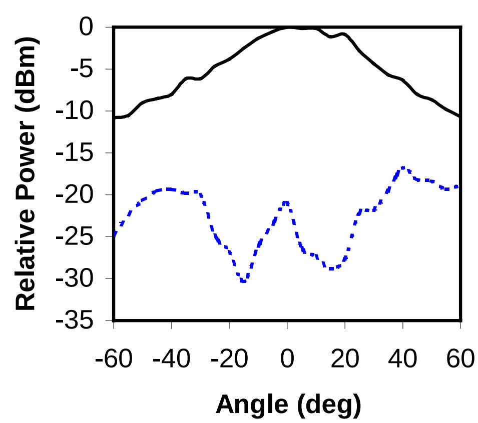


Fig. 7(a): E-plane radiation pattern. The solid and dashed lines indicate the co-polarization and cross-polarization patterns respectively.

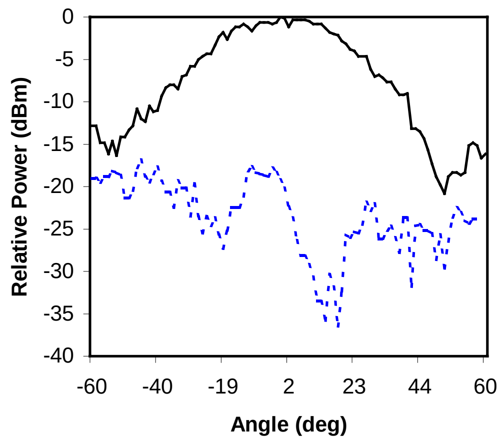


Fig. 7(b): H-plane radiation pattern. The solid and dashed lines indicate the co-polarization and cross-polarization patterns respectively.

The grid oscillator for the University of Hawaii's CubeSat will be a scaled version of the one shown in Fig. 6. Due to the size and weight constraints of the CubeSat, this grid oscillator must be a very compact and lightweight structure.

The simulation in Fig. 8 shows that with a unit cell size of 6x6 mm, substrate thickness of 0.157 cm, and ε_r = 10.2, oscillation can be achieved at 5.76 GHz. This is very close to our desired frequency of 5.85 GHz, for which we acquired an amateur radio frequency license.

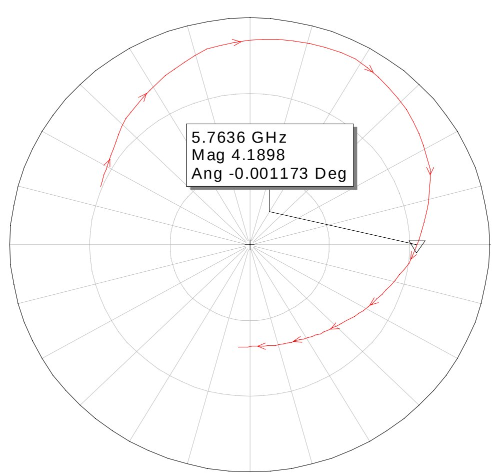


Fig. 8: Simulated loop gain for the grid oscillator for the CubeSat. Oscillation is achieved at 5.76 GHz, close to the goal of 5.85 GHz.

We are currently in the process of fabricating the grid oscillator for the CubeSat. A 6x6 transistor array was chosen to supply sufficient power to be detected by the ground station. The link analysis using the Friis Formula is shown in Fig. 9. [7] If each transistor is biased at 1.5 V and 10 mA, the entire grid will require 540 mW of DC power. Assuming 20% DC-RF conversion efficiency, the transmitted power is estimated at 20.33 dBm.

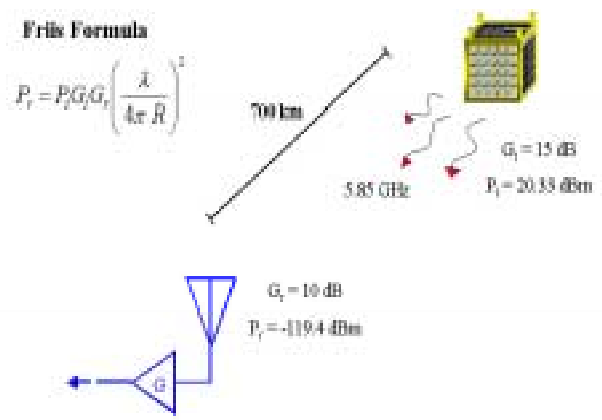


Fig. 9: Link analysis for grid oscillator.

V. Physical Specifications and Integration

An important aspect of the design was achieving certain physical specifications required from the overall CubeSat perspective. The areas of consideration were: mounting schematics, circuitry layout, and weight.

There were several constraints for the mounting of the grid oscillator since the grid requires the placement on the exterior of the cube. The first goal was to minimize the physical size in order to share a face of the cube with a solar panel for maximization of power, as shown in Fig. 10. This was dependent on the unit cell size, since a 6x6 array was previously selected.

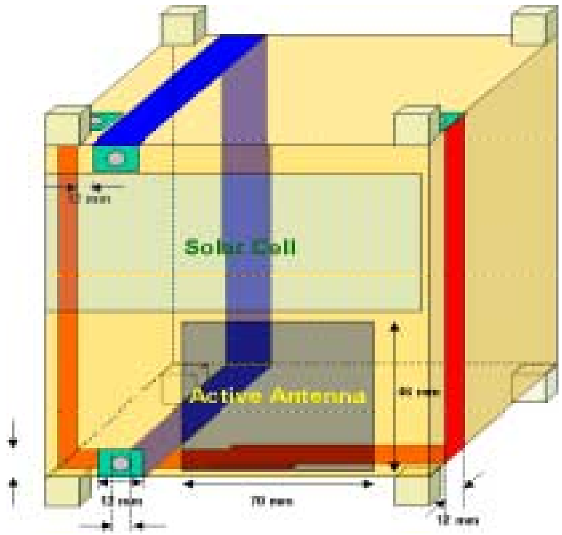


Fig. 10: Proposed placement of grid oscillator on top face of cube.

The grid will be mounted to a face of the satellite using an adhesive and possibly screws. The nylon screws are proposed since it will not affect the grid oscillator signal, and will only be used if necessary. Also being looked into is the use of a conformal coating to protect the oscillator in space.

A more detailed mounting schematic is shown in Fig. 11. An important point to note is the extension of the antenna structure beyond the housing wall. The launch requirement provides a 6.5-mm buffer externally from the face of the cube. The current design uses approximately 3 mm of that buffer. It is estimated that the grid oscillator will be 5x7 cm in size and weigh approximately 26 g.

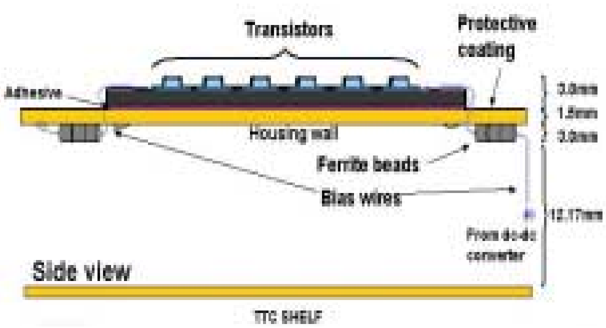


Fig. 11: Side view of the CubeSat showing the placement of the grid on the top face of the cube.

Another major concern was with the integration into the overall CubeSat operation. The grid oscillator involves the collaboration with several groups for successful operation: Power Generation and Distribution (PGD), Data Command and Handling (DCH), and Mechanical Structures and Analysis (MSA). The PGD Group will be supplying power for operation of the grid, as DC bias voltages are required for turning on the transistors on the oscillator. The signal that is generated and sent from the satellite down to earth will be Morse-coded for identification; DCH will assist with the sequencing of turning the oscillator on and off for coding. Finally, the MSA Group will be involved in the final mounting design and actual physical implementation.

To protect other sections of the satellite from a grid oscillator failure, fuses will be implemented in several areas. Fig. 12 shows the proposed method of implementing fuses. Different configurations are being looked into to reduce the amount of fuses necessary while maintaining safe operation.

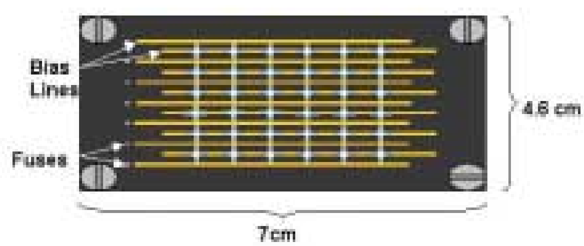


Fig. 12: Grid oscillator with fuses connected to each bias line to protect other components of the CubeSat.

Two DC-DC voltage converters will be used to provide the specific biasing required to turn on the grid oscillator. To turn on and off the drain bias (for coding) DCH can make use of the built in shutdown capability of the voltage converter chips.

VI. Conclusion

The active antenna onboard the University of Hawaii's CubeSat will lead the way for future, more data-intensive missions. It has been shown that an antenna of this type is capable of transmitting at high frequencies while remaining within design constraints by maintaining a compact, lightweight, and low-profile structure and operating at approximately half a watt of DC power.

VII. Acknowledgements

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