Multi-Frequency Antenna design for Space-based Reconfigurable Satellite Sensor Node

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Abstract— The paper investigates the antenna design to be applied in the ESPACENET sensor node. The project involves a network of autonomous pico satellites working at a large number of communication standards and as passive radar sensors for earth observation. They would form the next generation of "eyes in the skies"; looking out for natural disasters, helping in the survey and effective utilization of natural resources and also form a seamless network of global communication which will have the potential to evolve itself with the growing demands of tomorrow's world. We discuss the need for a multiple frequency broadband antenna which would help cover a larger range of microwave frequencies enabling the antenna to work as both a communications antenna and a sensor device.

1. Introduction

The planet that we live in has become a very unpredictable environment, the extremes of heat and drought, storms, wind, and rain. With a growing earth population the impact of these changes leads to a higher loss of life. Hence to prevent these natural disasters we need a better understanding of the complex interactions between the earth's surface and the atmosphere.

Microwave interferometry gives us this advantage to study the earth's atmosphere in terms of range measurement, 3D imaging giving improved penetration through dust, smoke and fog, navigation and collision avoidance systems and the measurement of the soil moisture content which is a key variable of the water and energy exchanges in the atmosphere. It would be ideal to have a single system that could cover the wide range of frequencies expected to be used for sensory applications like interferometry; as well cover the communication frequencies. In section II we shall discuss the various space applications and the frequency ranges expected for each, followed by a short introduction of the ESPACENET sensor network [1], in section III, and its need for a multiple frequency antenna and then in section IV we identify the different antenna designs and then compare them with respect to their scattering parameters. We conclude with the results for which we seem is the best design which would cater to the applications we foresee.

2. Space-Based Radar

Space-based radar refers to space-borne radar systems that may have any of a variety of purposes. A number of earth-observing radar satellites, such as RadarSat, have employed synthetic aperture radar (SAR) to obtain terrain and land-cover information about the earth [2].

Normal radar emits pulses with a very narrow range of frequencies. This places a lower limit on the pulse length (and therefore the resolution in the distance direction) but greatly simplifies the electronics. Interpretation of the results is also eased by the fact that the material response must be known only in a narrow range of frequencies.

Ultra wideband radar emits very short pulses consisting of a very wide range of frequencies, from zero up to the radar's normal operating frequency of 5.3 GHz as in the RadarSat-I. Such pulses allow high distance resolution but much of the information is concentrated in relatively low frequencies. Thus such systems require very large receiving apertures to obtain correspondingly high resolution along the track. This can be achieved with synthetic aperture techniques [3].

To enable the study of such a wide dynamic range of frequencies we need ultra wide band frequency antennas which will be able to work not only in the narrow band applications of data, voice and imaging, but at the same time work as broadband antennas for the radar applications.

There are a number of factors that must be taken into account when considering the antennas for the space

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applications; one would be the impedance versus frequency behaviour. If the antenna impedance varies with frequency then the signal spectrum entering the antenna will be modified causing signal distortion. Another important factor is the aperture of the radar; aperture is defined as the measure of the area or the physical size of the antenna. The larger the area the more signal it can collect which means a higher gain.

Some key frequencies used by low earth orbit satellites for earth observation are in the range of 350-3500GHz and for data relay in geostationary orbit with two independent antenna working for 17.7-20.2 GHz in transmission and 27.5-30.0 GHz in reception [4].

Telecommunication satellites over the EU and USA are based in geostationary orbits and use one antenna for every region of coverage and communicate within the ranges of 11.45-12.75 GHz for transmission and 14.0-14.5 GHz for reception. These are multispot antennas and use a lot of power of the node whilst making use of these multiple antennas.

The ability to measure atmospheric and surface parameters using satellites based passive microwave observations is determined by the absorption spectra of atmospheric gases, the absorption and scattering of hydrometers, and the sensitivity of surface reflectivity and emissivity to various physical parameters. The dominant gas absorbers in the troposphere are water vapour and oxygen, with resonances at 22.235, 50, 61, 118.75, 183.31 and 325.15 GHz. Other trace gases that exhibit strong microwave resonances in the stratosphere and mesosphere include O_3, CO and N_2O [5].

Surface observables include soil moisture using channels near 1.4 GHz, sea ice coverage using 6, 10, 18, 37 and 90 GHz, sea surface temperature using 6-37 GHz, sea surface wind speed using 10-37 GHz and snow cover using 6-37 GHz [5].

Such wide varieties of antennas are supported with the development of multifeed reflector antennas, in parallel to high-efficiency horns and low loss waveguide beam forming networks.

With the idea of having smaller low power autonomous network of satellites which are controlled by an biologically inspired evolvable algorithms that would learn from problem solving a number of key system and network parameters to increase the efficiency and life time of the network.

We have mentioned the number of applications undertaken by today's larger telecommunication and observation satellites and replicating the same for a smaller satellite is not feasible since we cannot support a large number of devices and their power requirements. Which lead us to developing an array of multi-frequency antennas onto a single device or chip that can be deployed onto these micro or pico satellites that cover the whole range of frequencies in our application. There aren't any implementations on chip level for a multi-standard device and micro antenna implementations for a satellite, hence the need for us to develop such a technology.

This also leads to the fact that a single cluster can perform a number of operations unlike that of our traditional larger satellites which would only work in one mode at a time. If failures do persist it would be difficult for a single system to recover from a fault whilst the network of satellites would reconfigure individual nodes to overcome the failure and assist in the application to keep running in spite of hardware failures.

The cluster would also be spread out on a wider region in space acting as a larger aperture and using SAR techniques to get better resolution images and accurate information than its larger cousins. So it would be beneficial for us to substitute one large satellite with cluster of smaller satellites, forming the basis of virtual satellite missions required for effective earth observation and disaster monitoring.

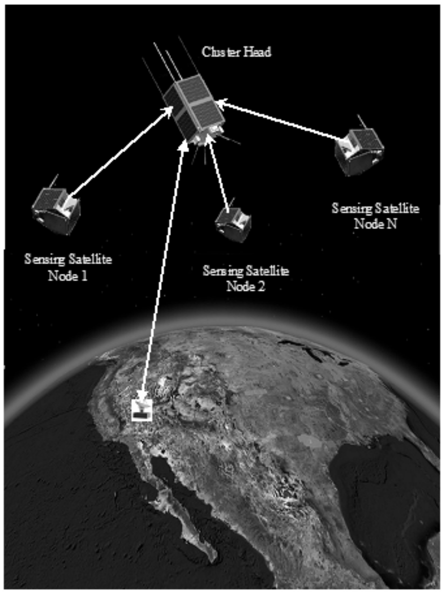

Figure 1. **Cluster of Multiple satellites for virtual satellites missions**

Key antenna performance goals will most likely require simultaneous beams, increased bandwidth/multiple operating bands, full coverage electronic scanning, very large gain, and low side lobes.

Existing electronically-steerable phased arrays have been designed and constructed on rigid panels with heavy and expensive manifolds. Current antenna design and manufacturing approaches will not meet the projected performance or cost goals for space based radar applications. The electronics are highly customized and

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expensive. For example, current solid state phased array radars use individually packaged transmit/receive modules that were developed by an industry that has its heritage in airborne active apertures [6].

Further on we will see how our multi-frequency antennas arise to solve the issues of saving power, covering a wider spectrum of frequencies and maintain a highly reliable autonomous network of satellites.

3. ESPACENET Sensor Network

In the ESPACENET project [1] we are making use of such formation flying pico satellites that form clusters, each cluster flies in a low earth orbit. As each satellite passes over its designated area of observation it would configure itself to capture the data, as it flies past, the next satellite entering the area would take over the observation.

Our cluster of pico satellites are divided into a hierarchy of sensor nodes which form the basis of the sensor network and controlling these nodes is a single cluster head.

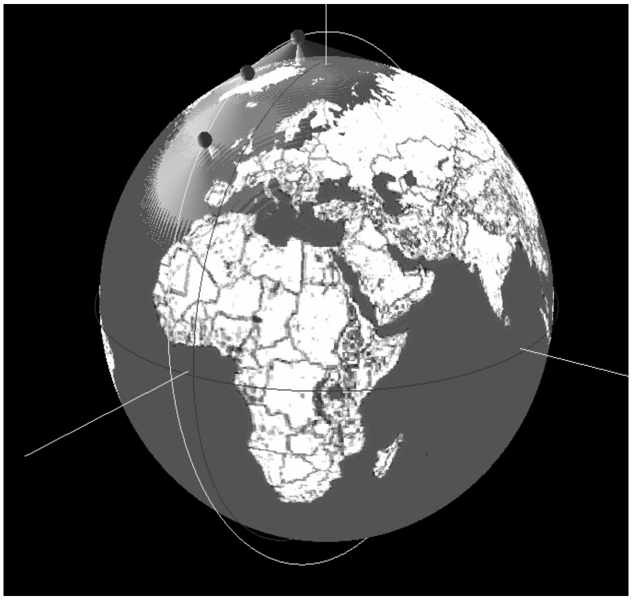

Figure 2. **Proposed Orbit for Sensor Nodes [3]**

Each sensor node will be performing its tasks of either image sensing or radar mapping and passes this data to its cluster head which will in turn is simultaneously collating data from the other sensor nodes to be passed to the ground station. Running on all the satellites in the seamless fabric of space is the autonomous multi-objective algorithm which is constantly monitoring each satellite from a node and network perspective. It will be responsible for taking decisions based on the health of the population and the application each cluster or individual node has to perform.

Due to this feature of distributed computing we need to constantly be sending packets of information along with the regular sensor data being sent around the network. All these applications will be running concurrently on different communication protocols which have different frequency bands.

Considering the size of the satellites it would not be feasible to have multiple antennas working for protocols instead have a single antenna based on frequency independent antennas with the choices consisting of spirals, conical spirals, log periodic dipole arrays, etc [7]. In the following section we shall look at the various antenna designs and compare them to the number of frequencies they can effectively cover and if they would be applicable in an array structure.

4. Antenna Designs

Many widely used antennas, e.g., monopoles, loops, Yagi-Uda arrays, etc. are inherently narrow band devices. Typical broadband antennas include axial mode helices, biconical dipoles, optically based antennas (e.g., parabolic reflectors) and frequency independent antennas (spirals, conical spirals, log periodic dipole arrays, etc.). In many cases, while these antennas offer wide impedance bandwidths, the radiation location can move with frequency, this causing time dispersion in the radiated signal.

There are a number of factors that must be taken into account when considering antennas for UWB applications. One is the aforementioned impedance versus frequency behaviour. If the antenna impedance varies with frequency then the signal spectrum entering the antenna will be modified causing signal distortion [8].

To overcome these variances we can look towards frequency independent antennas whose geometries are specified by angles and whose performance is invariant of the electrical dimensions.

To meet the frequency independent requirement in an electromagnetic structure like an antenna, we would require that the current attenuate along the structure and be negligible at the point of truncation. For radiation and attenuation to occur, charge must be accelerated and this happens when a conductor is curved or bent normally to the direction in which the charge is travelling. Thus, the curvature of a spiral provides frequency independent operation over a wide bandwidth [9]

We have explored various designs like the log spiral antenna, helical antenna and a square spiral antenna using MicroStripes [10], an electromagnetic simulation software. All the designs are probe fed micro electromechanical structures (MEMS) controllable antennas. The advantage of this design is that an array of such frequency independent antennas can be used for beam forming and adapt the overall radiation pattern in a desired direction that would be

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applicable in scanning earth over a wide range of frequencies.

4.1 Log Spiral Antenna

The first design is that of a Log Spiral Antenna, with the outer diameter of 800μm and inner diameter of 60μm, shown figure 3, which is equation of a logarithmic spiral [9], is given by

$$r=a^{\theta}, \quad \ln r= \theta \ln a \qquad (1)$$

Where *r* = radial distance to point P on spiral, *θ* = angle with respect to x axis, and *a* = constant. The results are given by the scattering parameters in figure 4.

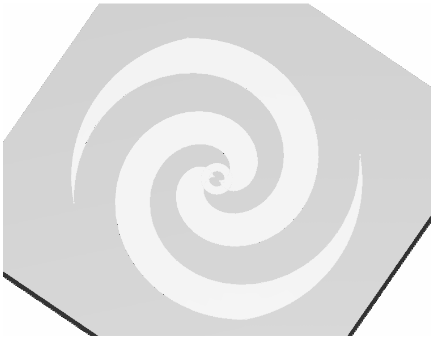


Figure 3. **Layout of a Log Spiral Antenna**

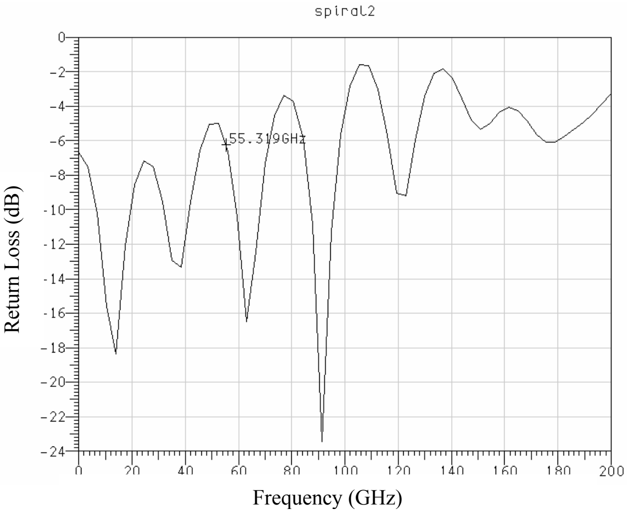


Figure 4. **Scattering parameters for Log Spiral Antenna**

We can observe that the scattering parameters have a number of peaks which show the possible resonant frequencies the antenna would work effectively. However the radiation patterns shows that the direction of the beam was scattered with high loss at lower frequencies with close to zero efficiency and having a maximum efficiency of 26% up to a frequency of 122 GHz then reducing again.

4.2 Helical Antenna

A helical antenna, shown in figure 5, operated in the normal mode is physically smaller compared with the wavelength. We designed the helical antenna with increasing spacing between the arms to have increased directivity.

The smallest arm is 30μm while the largest dimension is 840μm. For this particular design we have only a single turn although in practice the directivity of the antenna is directly proportional to the number of turns used.

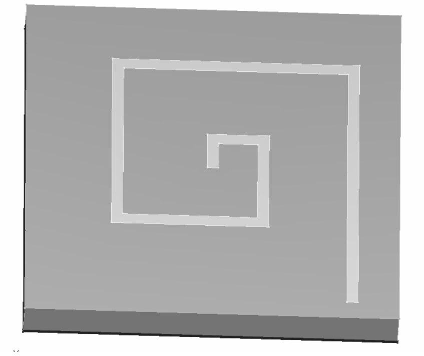


Figure 5. **Layout of a Helical Antenna**

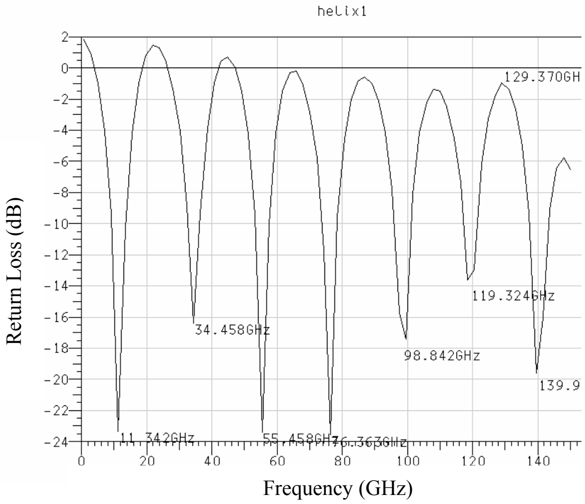


Figure 6. **Scattering parameters for Helical Antenna**

The Scattering parameters, figure 6, show that we have more resonant frequencies, which when compared to the log spiral antenna are fairly consistent characteristics over a larger number of intervals of the frequency spectrum. However the radiation pattern was not desirable as it would have been impractical to be used in an antenna array.

4.3 Square Spiral Antenna

This is a more compact form of the helical antenna where the arms are equidistant from each other. The width of the arm is 30µm and 3 complete turns were made, figure 7, to make the final antenna. The scattering parameters, figure 8, were observed to be quite similar to the helical antenna and the 3D radiation pattern was consistent through out the dynamic range of frequencies and it also resulted in a higher efficiency in comparison to the previous two designs in this case the efficiency varied from 7-42% over the range of 2-150 GHz. This meant that the antenna was fairly frequency independent and was an ideal design for the phased antenna array.

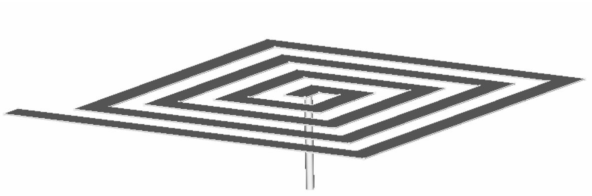


Figure 7. **Layout of the Square Spiral Antenna**

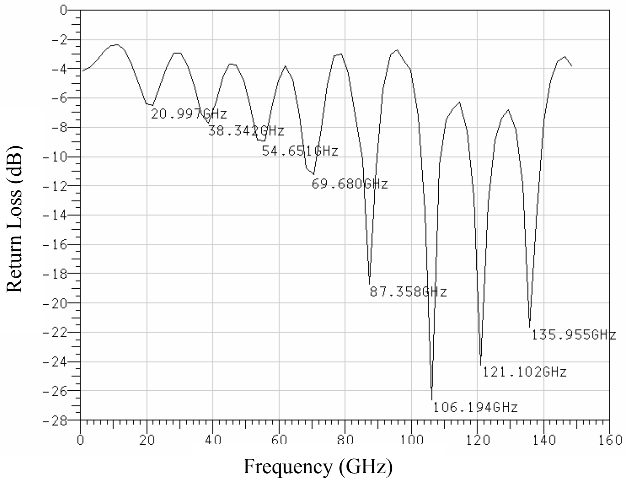


Figure 8. **Scattering parameters for Square Spiral Antenna**

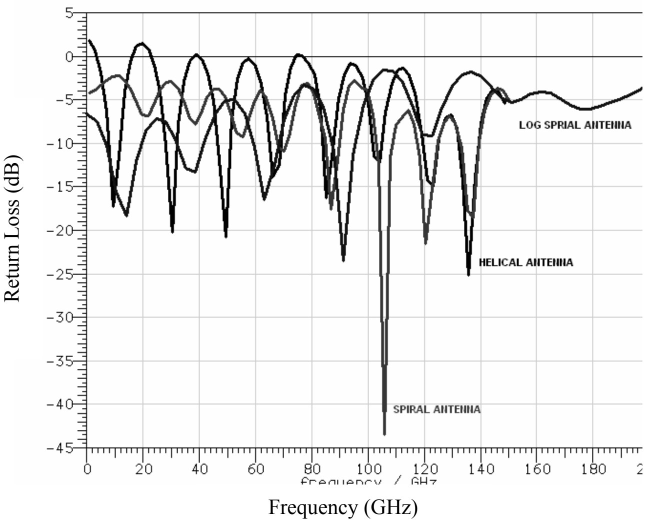
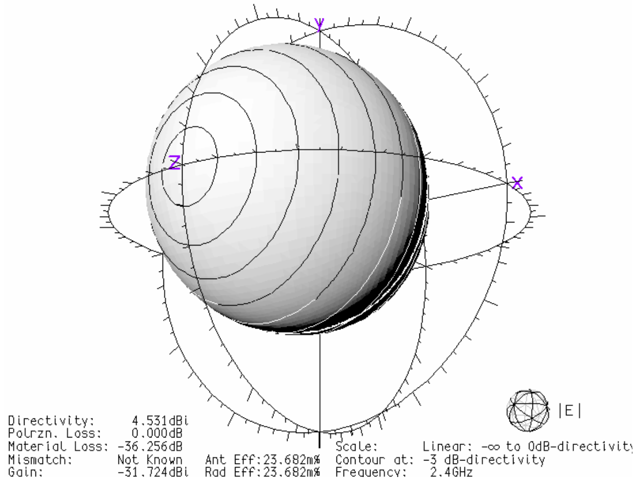


Figure 9. **Comparing return curves for all Antennas**

Comparing the results for scattering parameters for all the antennas, shown in figure 9, we can see that the return-loss curves for all three designs are fairly similar making them frequency independent antennas. However only the square spiral had a consistent radiation pattern and efficiency twice more than the other two designs, figure 10-13, and for this reason it would make an ideal choice to be used in an antenna array since we would be able to predict the direction of the main beam when we apply a phase shift to the individual antennas.



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Directivity:     4.531dBi
Polrzn. Loss:    0.000dB
Material Loss: -36.256dB
Mismatch:      Not Known   Ant Eff:23.682m%  Scale:        Linear: -∞ to 0dB-directivity
Gain:          -31.724dBi  Rad Eff:23.682m%  Contour at: -3 dB-directivity
                                             Frequency:    2.4GHz
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Figure 10. **3D Radiation pattern of Square Spiral at 2.4 GHz**

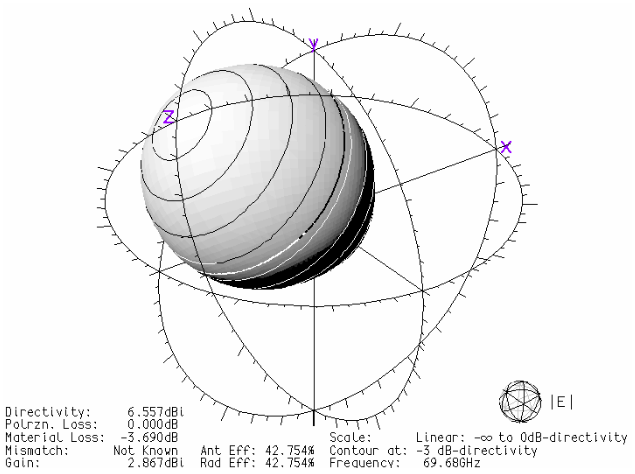

Figure 11. **3D Radiation pattern of Square Spiral at 69.68 GHz**

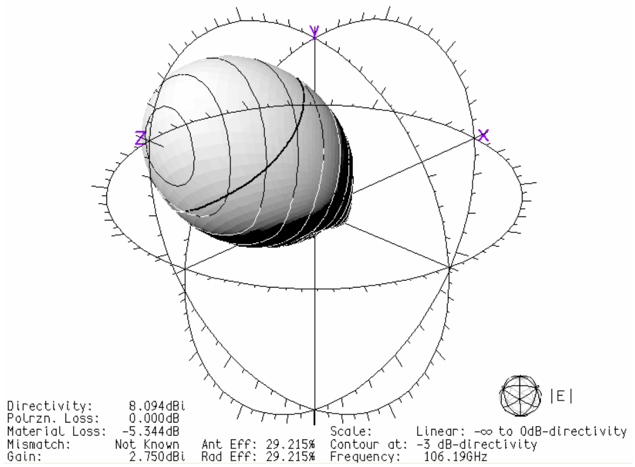

Figure 12. **3D Radiation pattern of Square Spiral at 106.68 GHz**

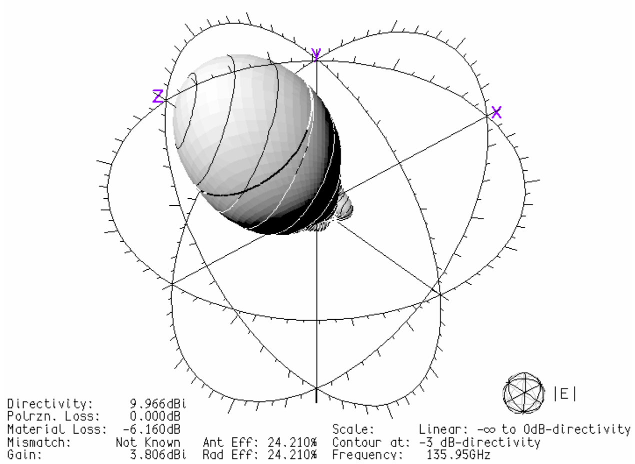

Figure 13. **3D Radiation pattern of Square Spiral at 136.54 GHz**

5. Conclusion

We have designed different multi-frequency antennas. Comparing the obtained results we selected the square spiral antenna to be used in our application of space-based sensor satellites. The antenna was designed with the goal of maximum frequency coverage with an acceptable efficiency and radiation pattern. It can be used in a phased array antenna, and have been effectively simulated to create highly directive antenna arrays.

It must be noted that each antenna is in the micron scale and hence an array of such small antennas will lead to a very small yet independent beam forming antenna covering the communication and sensor range for the satellites application. These miniature antennas will help develop autonomous pico satellites that would one day replace today's larger communication and earth observation satellites.

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