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Microstrip Yagi Array for MSAT Vehicle Antenna Application

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ABSTRACT

A microstrip Yagi array has been developed for the MSAT system as a low-cost mechanically steered medium-gain vehicle antenna. Because its parasitic reflector and director patches are not connected to any of the RF power distributing circuit, while still contributing to achieve the MSAT required directional beam, the antenna becomes a very efficient radiating system. With the complete monopulse beamforming circuit etched on a thin stripline board, the planar microstrip Yagi array is capable of achieving a very low profile. A theoretical model using the Method of Moments has been developed to facilitate the ease of design and understanding of this antenna.

INTRODUCTION

A major element of the Mobile Satellite (MSAT) program has been the development of several types of medium-gain L-band vehicle antennas. Currently, two medium-gain antennas have been developed and field tested with successful results. One is the electronically steered planar phased array[1], and the other is the mechanically steered 1x4 tilted microstrip patch array[2]. The phased array offers the advantage of low profile (one-inch tall) and beam agility at the expense of higher production cost. On the other hand, the mechanically steered 1x4 array antenna offers the lowest production cost with the highest profile (six-inch tall).

To combat the disadvantages of high cost or high profile of the above antennas, a new antenna concept is being introduced, which not only offers both the advantages of low profile and low cost, but shows excellent efficiency in its beamforming circuitry as well. This antenna is a mechanically steered planar Microstrip Yagi array[3]. It is composed of twelve parasitic director and reflector patch elements and four driven elements. The reflector and director patches, based on Yagi's principle[4], tilt the array's broadside beam towards endfire for satellite pointing. Because only the few microstrip driven element patches are directly connected to and driven by the RF power distributing circuitry, the complexity and RF loss of the power distributing circuit are dramatically reduced, resulting in improved antenna noise temperature and antenna gain. The overall height of the antenna is only 1.5 inches, which includes both the RF portion and the mechanical rotating platform. The rotation in azimuth is accomplished by a thin pancake motor. The control of this motor, or the beam pointing, is done by a monopulse system that is uniquely designed for the

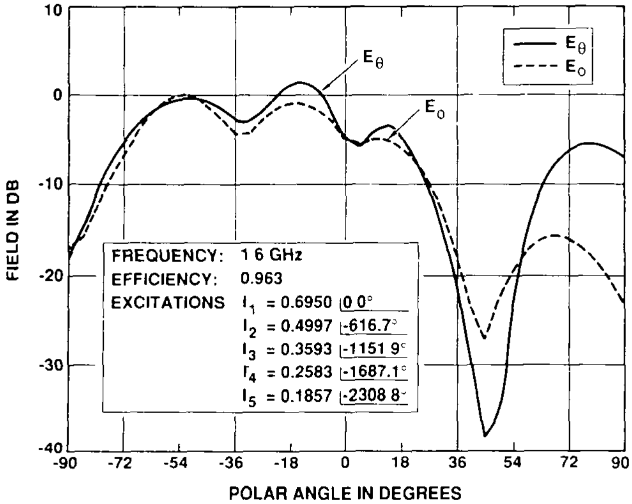

Figure 6. Computed elevation patterns of the 5-element ANSERLIN array at 1.6 GHz.

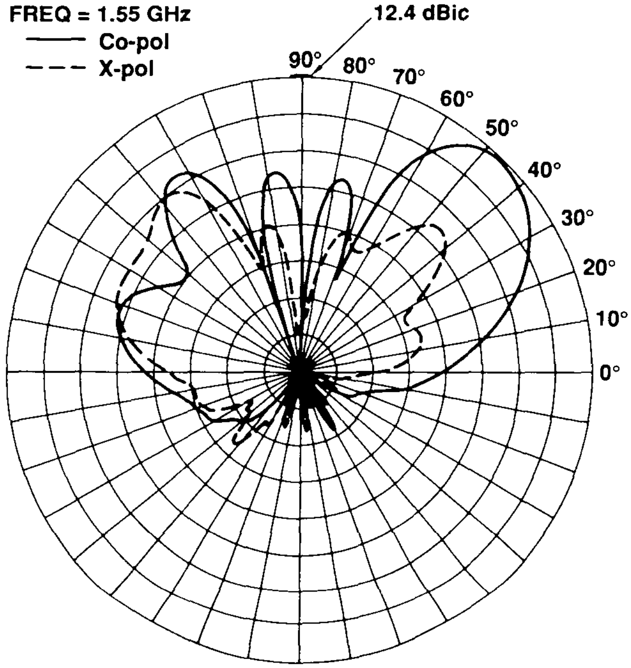

Figure 7. Measured elevation patterns of the 4-element ANSERLIN array at 1.55 GHz, on a 48" x 56" ground plane.

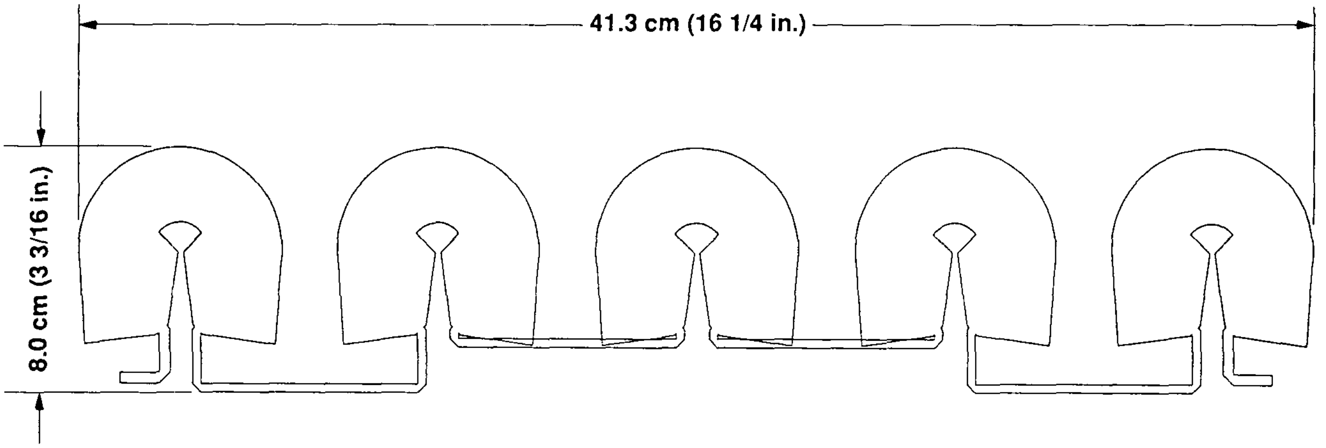

Figure 8. Outline of the symmetric 5-element array.

communication antenna to provide simultaneous transmit and receive signals.

To facilitate the ease of design and have a complete understanding of this microstrip Yagi array, a theoretical model based on the Method of Moments has been developed[5]. The purpose of this article is to present both the theoretical and experimental results of the MSAT microstrip Yagi planar array antenna, as well as its monopulse satellite tracking system.

Principle of Microstrip Yagi Array

The microstrip Yagi array antenna, as illustrated in Figure 1, consists of a driven patch element and a few parasitically coupled reflector and director patch elements. It utilizes the same principle as a conventional dipole Yagi array where the electromagnetic energy is coupled from the driven element through space into the parasitic elements and then re-radiated to form a directional beam. The sizes of the parasitic dipole elements and their relative spacings are designed so that the phases of all the elements are coherent toward the end-fire direction (in the direction of the director elements). For the microstrip patches to have the same Yagi effect as the dipole elements, the adjacent patches need to be placed very close to each other so that significant amount of coupling can be formed through surface wave and radiation mechanisms. It was found experimentally[3] that the gap distance between two patch edges should be equal to or less than the dielectric substrate thickness. Since the amount of surface wave is a strong function of the dielectric constant and substrate thickness, the pattern shape of the microstrip Yagi array is also a function of these two parameters. In addition, the sizes of the parasitic reflector and directors are factors in determining the pattern shape and beam direction. When the size of the parasitic patch is different from the resonant dimension (driven element size), a reactance component is added into the radiation impedance of this parasitic patch, which introduces an additional phase to its radiation field. It is this phase, together with the coupling phase, that contribute to the Yagi array's beam tilt from its broadside direction. Because the microstrip antenna requires a ground plane, the beam direction of the Yagi never becomes true end-fire. This beam tilt angle from the broadside, as explained above, is a function of dielectric constant, substrate thickness, patch separation, and reflector and director sizes. In general, the patch separation and parasitic patch size govern the relative phase, while the gap distance determines the current amplitude of each Yagi element.

Several important and interesting characteristics of the microstrip Yagi antenna have been found through experiments, first is that, if good circular polarization (c.p.) is desired in the Yagi's main beam region, the phase difference between the two orthogonal feeds needs to be deviated from the conventionally required 90-degree. This is due to the fact that the main beam is no longer in the broadside direction, and the E-plane and H-plane coupled fields have different coupled phase terms. Figure 2 shows the circularly polarized microstrip Yagi array pattern where the two orthogonal probes are fed 90° apart in phase. Figure 3 illustrates the pattern of the same array with improved c.p. when the two probes are fed 115° apart in phase. The second interesting finding is that, because the E-plane (along the array axis) has a much stronger surface wave coupling than the H-plane, the input impedance of the E-plane probe is strongly affected by the parasitic patches. As a result, to achieve the nominal 50 ohm input impedance match, the position of the E-plane probe in the driven element of the Yagi array is different than that of the classical single microstrip patch. This re-adjusted feed position has been found to be toward the edge of the patch. Finally, the microstrip Yagi array has a wider bandwidth than the driven element by itself. This is because the parasitic director and reflector, having different sizes from the driven element, are causing a "log-periodic frequency independent" phenomenon to occur. Figure 4 is a Smith chart that gives the input impedance as a function of frequency for a single patch (2.2-inch square) with dielectric constant of 2.5 and substrate thickness of 0.25 inch. It shows a single-loop response with a relative narrow bandwidth. Figure 5 gives the input impedance plot of the same element with H-plane coupled parasitic director and reflector patches. The plot shows a double-loop response which has a double-resonance and covers both the MSAT's transmit and receive frequencies.

Theoretical Analysis

The microstrip Yagi array is analyzed using the full-wave moment method solution, similar to solutions that have been previously used for a variety of microstrip antenna problems[5]. Since the parasitic elements in the Yagi are excited solely through mutual coupling from the driven element, it is necessary that the analysis be able to predict mutual coupling in an accurate manner. Surface wave prediction is especially important here because the gap distance between adjacent patches is relatively small and hence, cause a strong surface wave coupling. The solution also models the probe feed, as well as the circularly polarized dual feeds.

A computer code has been developed for the analysis of the microstrip Yagi geometry having one driven element and up to four parasitic elements with arbitrary sizes and spacings. The software uses the moment method solution to compute the currents on the patch elements; from these quantities the input impedance, far-field patterns, and directivity can be determined. The analysis has shown that the director patch has a much stronger coupling than the reflector's coupling from the driven element. This is why, as illustrated in Figure 1, two directors are used to effectively tilt the beam, while only one reflector is needed. Adding more reflectors to the array does not achieve any significant effect. The comparison between the calculated and measured patterns of a single column of microstrip Yagi array at the frequencies of 1552 MHz are shown in Figure 6. The dimensions of this antenna are given in Figure 7. The agreement of the co-pol is quite good. The disagreement, especially in the cross-pol, is mostly attributed to the fact that the measurement was performed on a finite ground plane (5-wavelength diameter), while the calculation was carried out with an infinite ground plane.

Description of Antenna and Monopulse Beamformer

In order to meet the MSAT required minimum gain of 10 dBic between 20° and 60° elevation angles, four microstrip Yagi array columns are needed. The dimensions of each column are given in Figure 7, and the spacing between adjacent columns is 4.5 inches (0.61 wavelength at 1.6 GHz). The overall antenna aperture is a rectangle with dimensions of 10 by 17 inches. A 1/8-inch thick stripline monopulse beamformer located flush below the array, is designed to provide uniform excitations through feed probes to the 4 driven elements of the Yagi array. The RF block diagram of the overall antenna is shown in Figure 8, and its corresponding stripline beamformer layout is presented in Figure 9. A pictorial view of the fabricated antenna and beamformer is illustrated in Figure 10.

In Figure 9, the antenna feed network distributes RF power through Wilkinson dividers to the four driven elements of the Yagi array and establishes the required differential phase (115° in this case) between the two orthogonal feeds of each driven element. With the 180-degree hybrid coupler combining the incoming signals from the dividers, the monopulse sum and difference signals are generated. The bi-phase modulator implements a half-wavelength phase delay that is switched on and off by the pin diodes at a frequency around 1 KHz. With the simple single-line bias design, no slip rings are needed. Both the RF and diode control current go through a single-channel rotary joint. The modulated difference signal is coupled through a 10-dB coupler onto the sum channel, which are together sent down to the rotary joint. The purpose of the filter is to stop any portion of the transmit signal, coming up from the rotary joint, to the difference channel.

The antenna and the beamformer are together mounted onto a half-inch thick pancake motor that is controlled by the monopulse feedback pointing error signal to track the satellite. The complete antenna system is covered by a radome having a height of 1.5 inch and a diameter of 21 inches. Presented in Figures 11 and 12 are the measured antenna patterns at the receive and transmit frequencies, respectively. One noticeable shortcoming of the Yagi array is its high backlobe over a relative wide frequency bandwidth. Fortunately, investigation has led to the conclusion that these high backlobes will not present any adverse effect to the MSAT system in terms of tracking, multipath, or user interference. Certainly, power is being wasted in these backlobes. However, due to the excellent efficiency of the Yagi array with only 1.5 dB of loss in the beamformer, the required 10 dBic of gain has been achieved as shown in Figures 11 and 12.

Conclusion

A mechanically steered antenna with low cost, low profile, and low insertion loss has been developed for the MSAT system. This antenna combines the excellent efficiency of the microstrip Yagi concept and an elegant design of the monopulse beamformer to achieve the required antenna gain and high G/T ratio. Experiment has indicated that, with a slightly different array design, the microstrip Yagi antenna can also provide the required performance for the Canadian region where a lower elevation coverage is encountered.

ACKNOWLEDGMENT

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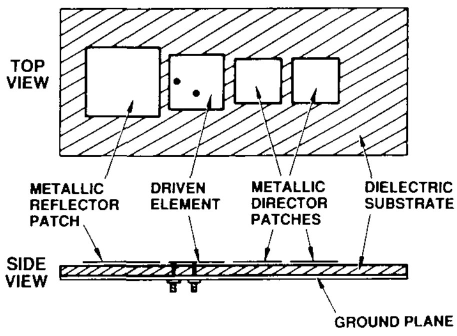

Figure 1. Microstrip Yagi array configuration.

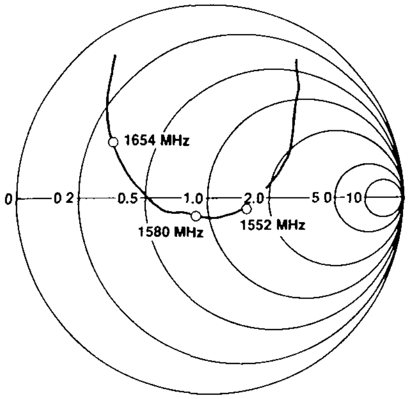

Figure 4. Input VSWR of a single microstrip patch.

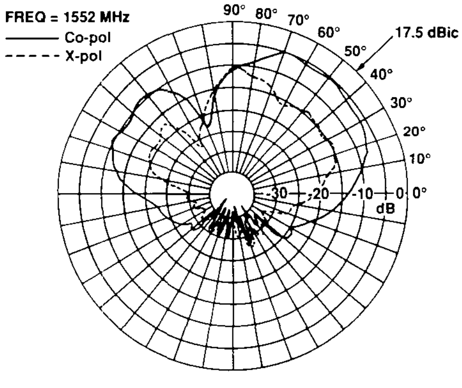

Figure 2. Measured C.P. microstrip Yagi array elevation patterns with 2 feeds separated 90° in phase.

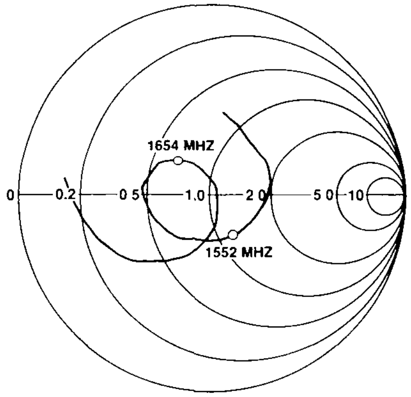

Figure 5. Input VSWR of a microstrip patch with parasitic Yagi patches.

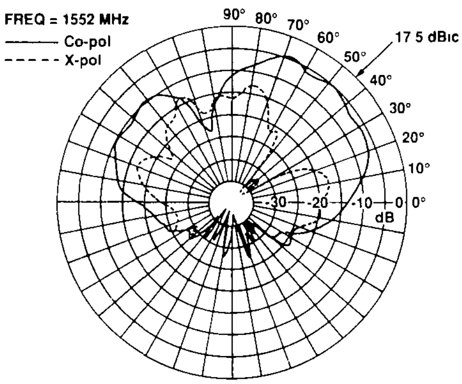

Figure 3. Measured C.P. microstrip Yagi array elevation patterns with 2 feeds separated 115° in phase.

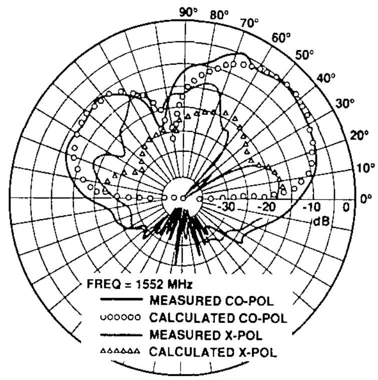

Figure 6. Comparison of calculated and measured patterns of the microstrip Yagi array shown in Figure 7 at 1552 MHz.

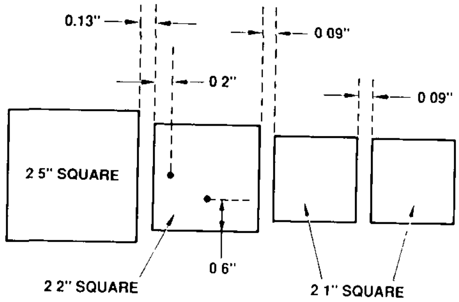

Figure 7. Dimensions of a single column L-band microstrip Yagi array.

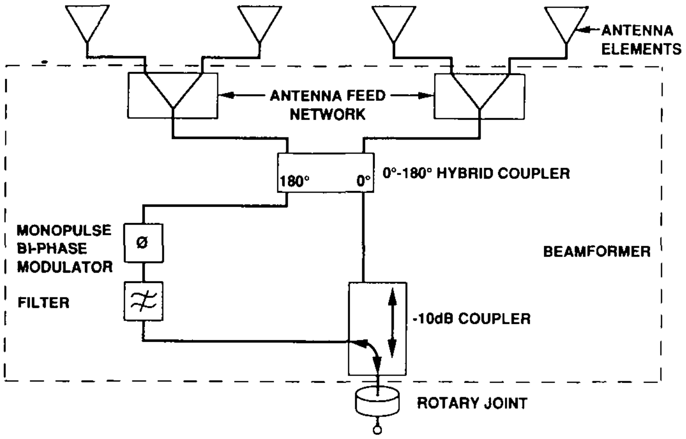

Figure 8. Block diagram of antenna and beamformer.

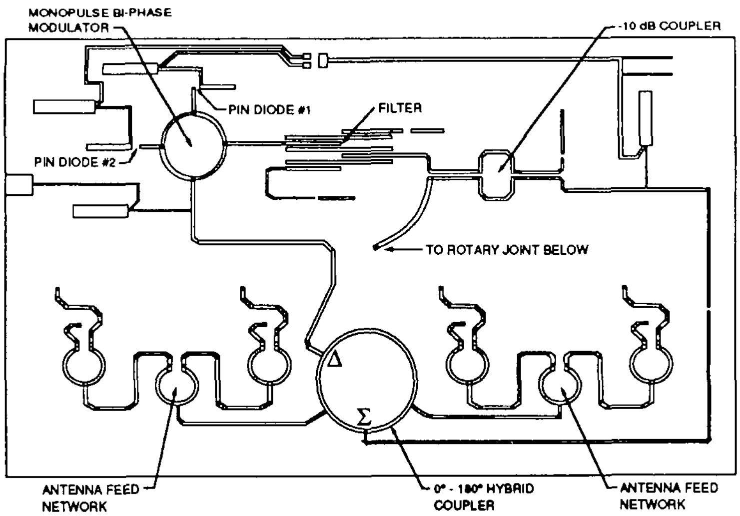

Figure 9. Stripline monopulse beamformer circuitry.

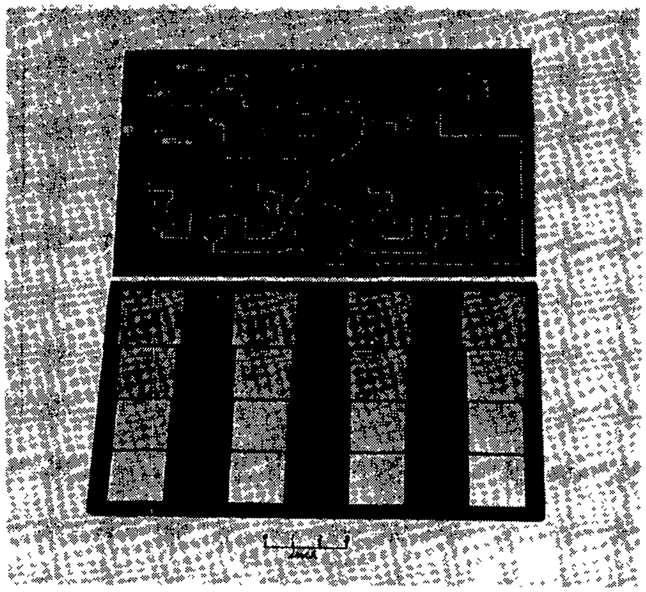

Figure 10. MSAT microstrip Yagi antenna and beamformer.

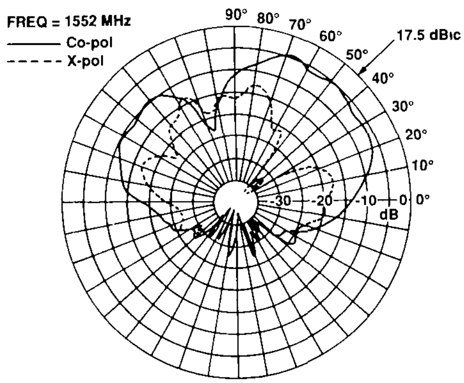

Figure 11. Measured elevation pattern of the MSAT microstrip Yagi antenna at 1552 MHz.

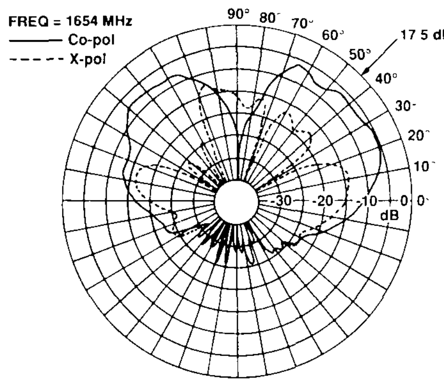

Figure 12. Measured elevation pattern of the MSAT microstrip Yagi antenna at 1654 MHz.