MICROSTRIP ANTENNAS FOR COMMERCIAL APPLICATIONS

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Abstract

The microstrip antenna, because of its small size, lightweight, low profile, and low manufacturing cost, is finding increasing applications in the commercial. sector of the industry. This article discusses briefly some of the antenna's technical features and presents several important examples of the antenna's commercial applications, such as mobile satellite communications, direct broadcast satellite services, global positioning system, medical hyperthermia usage, etc.

I. Introduction

Since the invention of the microstrip antenna[1,2] four decades ago, the demand for its application has been increasing rapidly, especially within the last two decades. However, these applications have been in demand mostly by the Department of Defense. Because of their extremely thin profile (0.01 to 0.05 wavelength), printed microstrip antennas have found heavy applications in military aircraft, missiles, rockets, and satellites. In the commercial sector, the adaptation of the microstrip antenna has not been as rapid, primarily due to the cost and the lack of demand. During the earlier years, the costs of the microstrip antenna's substrate material, its design, and manufacturing processes were considered non-competitive when compared to the monopole, helix, horn, or parabolic reflector. In addition, for example, the earlier popular terrestrial communication system's configuration and environment did not warrant the use of the microstrip antenna. During the last decade, however, the cost to develop and manufacture the microstrip antenna has dropped significantly, because of the maturity of the microstrip antenna technology, the reduction in cost of the substrate material and manufacturing process, and the simplified design process using the newly developed computer-aided design (CAD) tools. Furthermore, the current satellite communication applications benefit greatly from the small-size and low-profile of the microstrip antenna. For example, in a UHF cellular terrestrial communication system, with plenty of RF power and antenna real estate for its base stations, the mobile unit can perform adequately with a simple low-gain monopole antenna without any concern about its system gain margin being too small. However, in developing L-band mobile satellite communications[3], because of the limited spacecraft solar-battery power and spacecraft antenna size, the mobile vehicle terminal requires a higher gain antenna (on the order of 10 dBi) to ensure an adequate system link margin. To cover a wide elevation angular region from 20° to 60° above the "horizon with such a gain, an antenna, such as a horn, a helix, or a monopole array, will be too bulky to be mounted on top of a passenger automobile. A low-profile printed microstrip array not only offers an aesthetically pleasing appearance, but also yields a low manufacturing cost, especially when produced in large quantities.

This article discusses some of the microstrip antenna's technical features, its advantages, and disadvantages. Materials and fabrication techniques for commercial applications will also be briefly presented. Microstrip antenna applications in the areas of mobile satellite communications, the Direct Broadcast Satellite (DBS) system, and the Global Positioning System (GPS) will be highlighted. Nonsatellite-based applications, such as medical hyperthermia and remote sensing, will also be discussed.

II. Technical Background

This section presents the technical background of the microstrip antenna. The discussion is separated into three areas: features of the microstrip antenna, computer-aided design and fabrication, and materials.

A. Features of the microstrip antenna: A microstrip antenna[4,5], as shown in Figure 1, consists of a radiating metallic patch or an array of patches on one side of a thin, nonconducting, supporting substrate panel (thickness is 0.01 to 0.05 free space wavelength) with a ground plane on the other side of the panel. The metallic patch is normally made of copper foil or copper-foil plated with a corrosion resistant metal, such as gold, tin, or nickel. Each patch can be made into a variety of shapes with the most popular shapes being rectangular and circular. The supporting substrate material for an array application must be low in insertion loss with a loss tangent (also called dissipation factor) of less than 0.002. Generally, substrate materials[4] can be separated into three categories: (1) With a relative dielectric constant in the range of 1.0 to 2.0, the material can have the form of air, polystyrene foam, or honeycomb. (2) With a relative dielectric constant in the range of 2.0 to 4.0, the material consists of mostly teflon. (3) With a relative dielectric constant between 4 and 1.0, the material can be made of ceramic, quartz, or alumina. Generally, the trend is that the lower the substrate dielectric constant is, the lower the antenna cost and insertion loss will be.

A single microstrip patch can generally be excited either by a coaxial probe or by a microstrip transmission line, as shown in Figure 1. For an array of microstrip patches, the patches can be combined either with microstrip lines located on the same side of the patches or with microstrip or strip lines designed on a separate layer placed behind the ground plane. For the separate-layer configuration, each patch and its feed line are electrically connected either by a metallic thin post or by an aperture coupling slot[6]. In an array configuration, tens or hundreds of patch elements can be fabricated by a single low-cost etching process. In other words, each single patch element of the array does not need to be fabricated individually as many other types of radiating elements do. This microstrip array etching process leads to a lower antenna manufacturing cost.

There are advantages, as well. as disadvantages, associated with the microstrip antenna. By understanding each one of them, one can readily design a microstrip with the optimum efficiency, minimum risk, and lowest cost for a particular commercial application. The advantages of microstrip antennas when compared to conventional antennas, such as helix, horn, reflector, etc, are:

(1) The extreme low profile of the microstrip antenna makes it lightweight and it occupies very little volume of the structure or vehicle on which it is mounted. It can be conformably mounted onto a curved surface so that it is aesthetically appealing and aerodynamically sound.

(2) The antenna, when produced in large quantities, or an array with many patch elements, can be fabricated with a simple etching process, which leads to greatly reduced

fabrication cost.

(3) Dual-frequency operation is possible by using either dual-stacked patches[7] or a patch with a loaded diode[8] or a stub[9].

The disadvantages of the microstrip antenna are:

(1) The antenna has a narrow bandwidth (generally less than 3%). However, with technology advancement, 15 to 20 percent of bandwidths have been achieved. These are techniques that use multiple stacked patches, thicker substrates, external matching circuits[10], a sequential rotation arrangement[11,12], parasitic coupling[13], etc.

(2) Because of the small separation of the radiating patch and its ground plane (equivalent to small separation between two electrodes), the microstrip antenna can handle relatively low RF power. Generally, a few hundred watts of power or less is considered safe. However, depending on the substrate and metal thicknesses and the frequency of operation, a few kilowatts of power for microstrip lines at X-band have been reported[14]. It should be noted that for space applications, the power handling capability is generally less than that for ground application, due to multipacting breakdown[15].

(3) The microstrip array generally has a larger ohmic insertion loss than other types of antennas of equivalent aperture size. This ohmic loss mostly occurs in the dielectric substrate and the metallic conductor of the microstrip line power dividing circuit. It should be noted that a single microstrip patch element incurs very little loss because it is only one-half wavelength long. The loss in the power dividing circuit of a microstrip array can be minimized by using series feed techniques [5,16], waveguide and microstrip combined power dividers, honeycomb substrate, etc.

B. Computer-aided design (CAD) and fabrication: The choices of CAD software 15 to 20 years ago were limited and expensive. As a result, the "cut and try" method was relied on as a common solution to the design of microstrip circuits that resulted in longer development time, higher antenna cost, and inaccuracy in performance prediction. This situation, however, has changed radically since the performance of personal computers has improved significantly and a variety of CAD tools are available. A microstrip array is generally composed of two components: (1) the power dividing microstrip lines and (2) the radiating microstrip patch elements. Most of the CAD software tools have placed an emphasis on the design of microstrip lines, because they were developed not just for microstrip antennas, but geared more toward the circuit design of transmitter and receiver components, such as filters, hybrids, couplers, etc. Examples of these tools are Touchstone, Supercompact, Midas, LINMAC, and many others. Only a few CAD software tools were developed to handle both microstrip circuit lines and microstrip patch elements. The few that are known by the author are Micpatch, developed in Switzerland, using the transmission line multiport technique; Ensemble, developed by Boulder Microwave Inc. in Colorado, using the integral equation technique[17]; and the Micropatch package, developed by the University of Colorado, employing the multiport segmentation technique[18]. These packages not only aid in the array's circuit layout design, but also calculate the antenna input impedance, radiation patterns, and antenna efficiencies. Mutual coupling effects between patch elements are included in the analysis.

It should be pointed out that, because microstrip lines have relatively wider bandwidth (more than 10% bandwidth), all the above CAD tools can generally design the power dividing circuit of the microstrip array correctly the first time. However, because of the narrow band characteristics of the patch elements (less than 3% bandwidth), the CAD design will generally take one or two iterations for the actual patch element to resonate at the desired frequency. The inaccuracy in specifying the material parameters (i.e., substrate dielectric constant) by the manufacturers and unknown fabrication tolerances are two major contributors to the required iteration steps in designing the patch element. Nevertheless, the CAD tools can help the designer to complete a microstrip array design in several weeks, while the old "cut and try" method may take several months. Especially at the millimeter frequencies, the "cut and try" method, because of the extreme small patch size, cannot be accomplished by using a knife. Every iteration needs to be done by a complete etching process. Thus, without the CAD, the antenna development effort can become very costly and time consuming.

Once the CAD design is completed, the dimension data of the microstrip array is used to generate photographic film by using the very accurate laser optic technique. This photographic film is then used with chemicals to etch off the copper from the copper-clad substrate panel to form the desired microstrip array antenna. One etching process can yield hundreds or thousands of patch elements on a single panel. For example, if one desires to mass produce thousands of microstrip array antennas with each antenna consisting of hundreds of patch elements, the automated photographic and etching processes [5] can accomplish the fabrication accurately in several days. This is not possible with other types of antenna elements such as the horn, the helix, etc. This automated microstrip antenna fabrication process can, therefore, lead to low manufacturing cost.

c. Material: The purpose of the substrate material of a microstrip antenna is primarily to provide mechanical support for the radiating patch elements. There are a variety of types of substrate materials. As discussed in Section II A, the relative dielectric constant of these materials can be anywhere from 1 to 10. The most popular type of material is teflon-based, with a relative dielectric constant between 2 and 3. This teflon-based material, also called PTFE (polytetrafluoroethylene) , has a structural form very similar to, but has much lower insertion loss than, the fiberglass material that often is used for digital circuit boards. The selection of the correct material for the microstrip antenna, depending upon the applications, should be based on cost, insertion loss, thermal stability, dielectric constant, etc. For commercial application, cost is probably one of the most important criteria in determining the substrate type. For example, a single patch antenna or an array of a few elements may be fabricated on the lower-cost fiberglass material at the low end of the microwave spectrum, such as an L-band frequency; while a 50-element array at 15 GHz may have to use the higher cost, but lower loss, teflon-based material. For a large number of array elements at lower microwave frequencies, a nonmetallic honeycomb panel may be used as substrate to minimize insertion loss, antenna weight, and cost. A detailed discussion of substrate materials can be found in Reference [5] .

III. Applications for Mobile Satellite Communications

One of the most prominent communication systems that will utilize the microstrip antenna is the mobile satellite system. The examples given in Section I have clearly explained the reasons for applying microstrip antennas in a satellite-based communication system. The current terrestrial cellular system cannot provide complete coverage within a large global region, such as the United States. As a result, mobile-to-mobile communication would not be available in the rural area where no cellular station exists. A satellite- based system can fulfill this need by using either a few sets of fixed geostationary satellites or a large number of low Earth orbiting satellites. Two examples of the geostationary satellite systems are the already implemented International Maritime Satellite System ·(INMARSAT)[19] and the developing Mobile Satellite (MSAT)[3] system. Both systems operate at L-band frequencies. The INMARSAT has several different versions (Standards A, B, C, and D) of Earth terminals that use reflector-type antennas and are mostly intended for sea-going vessel applications. However, its recently developed Standard-M terminal, which is intended for land application, uses a briefcase-size microstrip array antenna. This antenna, developed by Glocom Corporation of Rockville, Maryland, uses six circular patches and provides 14.5 dB of gain.

The MSAT system has been studied internationally by entities such as Canada, Japan, the European Space Agency (ESA), Australia, and the United States. Because of the satellite's limited power, limited antenna size, and high altitude, its ground terminal requires a medium-gain (~10 dBi gain), rather than a low gain, antenna to satisfy the communication link requirements. Such a medium-gain antenna with a directive beam requires a satellite tracking capability to keep its beam pointed at the satellite while the vehicle is moving about. Two types of medium-gain antennas that use microstrip patches have been developed. One is the electronically steered phased array and the other is the mechanically steered array. Figure 2 presents two phased arrays with one developed by Ball Corporation[20] of United States, and the other one developed by Toyota Central R&D Laboratories of Japan[*']. Both antennas use dual-stacked patches to cover both the transmitting and receiving frequency bands with 19 elements.' Both antennas have a size of approximately 50 cm in diameter and 4 cm in height. Ball's study indicates that the phased array antenna, when produced in a volume of 50 thousand units in a 5-year period, would have a manufacturing cost of about U.S. $2000 per unit. Figure 3 presents a photograph of the Japanese antenna when installed on a passenger car. A similar phased array antenna system, developed by Ball Corporation has been installed on Boeing aircraft for commercial aeronautical satellite communications. Regarding the mechanically steered antenna, the Jet Propulsion Laboratory (JPL) of United States has developed a unique low-profile and efficient antenna system. This is the mechanically steered microstrip Yagi array[22]. Its photograph is presented in Figure 4. The array has a diameter of 48 cm and a height of 4 cm. For the same production quantity as the phased array, JPL has estimated that this mechanical antenna would cost approximately U.S. $400 per unit to the manufacturer. For both the phased array and the mechanically steered antennas, the microstrip radiator has demonstrated the capability of minimizing antenna's size and cost. Most of the costs in either antenna system are attributed to the beam scanning and tracking components, not to the radiator portion.

Low Earth orbiting satellite systems, such as the L-band IRIDIUM[23] system, proposed by the Motorola, Inc. , for example, would require multiple high-gain microstrip phased arrays on each satellite and low-gain omnidirectional antennas on the ground terminals. Each of the satellite's phased arrays has hundreds of microstrip patches. By printing all of these patches on a single flat panel, the fabrication process will lead to lower cost and the antenna system will require less volume and contribute less mass on the satellite. For the ground terminal, a low-gain omnidirectional antenna, such as a quadrifilar helix, will suffice. However, if antenna conformability to the vehicle's roof is required, the microstrip patch can certainly be used. A single patch excited at a fundamental mode or a higher-order mode can be considered. Circularly polarized, higher-order mode circular patch antennas[24] have demonstrated good omnidirectional coverage in the azimuth plane and optimum sectorial coverage in the elevation plane. A photograph of a fourth-order mode (TM_{41}) patch is shown in Figure

5, which gives calculated elevation patterns of three different patch modes.

IV. Applications for Global Positioning System (GPS)

The satellite-based GPS, initiated 30 years ago for military missions, has grown to have significant commercial applications. It has 24 satellites circling the Earth every 12 hours at an altitude of 20,200 km. Each satellite continuously transmits codes at two frequencies in the L-band. At any time, four of these satellites can together help a user on the ground to determine his precise position with an accuracy of 15 meters and the time to an accuracy of 100 nanoseconds. Thousands of these GPS ground terminal units were used by the U.S. Army in the Persian Gulf War for position finding, navigation, artillery fire control, etc. It is expected that millions of similar units will be used commercially by the general population for land vehicles, aircraft, and maritime vessels to determine their positions and directions.

The antenna needed for the ground terminal is a circularly polarized, omnidirectional, wide-beam, low-gain antenna. To minimize the antenna's size, mass, and costs at L-band, the microstrip patch radiator becomes the best candidate. Ball Corporation has developed a ceramic-loaded microstrip element, shown in Figure 6, that has a size of 5 cm x 5 cm, a thickness of 0.8 cm, and a weight of 85 grams. A higher dielectric constant ceramic loaded substrate is used to reduce patch size and to increase beamwidth. The dual-stacked-patch technology is employed to achieve the required two L-band frequencies of the GPS system. Toyota Central R&D Laboratories of Japan has also developed a microstrip GPS antenna, illustrated in Figure 7, that uses a stub-loading technology'[251] to achieve the dual-frequency capability with a single patch. This antenna was developed to be mounted on Toyota passenger automobiles for GPS navigational purposes. Figures 6 and 7, clearly show that it will be difficult to find another type of antenna to supersede the microstrip antenna's performance in terms of cost, mass, and size for GPS application.

V. Applications for Direct Broadcast Satellite (DBS) Systems

The DBS system has been providing television service to the general public in many countries. Its ground user antenna is required to have a high gain of about 30 dBi and to operate at the frequency of about 12 GHz. Conventional parabolic reflector antennas have been adopted currently by many users. However, the parabolic reflector, because of its curved bulky structure, cannot be easily hidden or surface mounted onto an existing building. In other words, it requires separate real estate for installation. As a result, a number of flat microstrip array antennas, have been developed for DBS with the features of being lightweight, easily installed on a building wall, aesthetically appealing, and low in manufacturing cost. Another advantage of using a flat low-profile antenna is that its performance is less affected by wind or snow than would be that of a parabolic reflector.

Japanese companies have dominated the development of flat DBS antennas. The **microstrip** type flat antennas developed by several Japanese companies are briefly discussed as follows. Yagi Antenna Corporation developed an array[26] with 1024 circular patch elements, which has an aperture size of 48 cm x 64 cm and a peak gain of about 33 dBi. NHK Science and Technical Research Laboratories has also developed a flat microstrip **antenna**[27] with increased bandwidth and efficiency. The antenna consists of 512 square patch elements with a size of 32 cm x 64 cm and a peak gain of 34 dBi. Other Japanese companies that developed similar DBS microstrip arrays are DX **Antenna**[28], Matsushita Electric Works[29], and Sony Corporation.

One recently proposed antenna that may become a competitor in the DBS terminal application is the microstrip **reflectarray**[30], which combines the technologies of the parabolic dish and the array. The feed of the **reflectarray**, as shown in Figure 8, illuminates the flat aperture that has many printed microstrip patch elements. These identical patch elements, having different phasor delay lines, are not connected by any power division lines. The re-radiated waves from these elements will be coherently directed toward a desired direction in accordance with the predesigned phasor delay lines. Unlike the curved parabolic reflector, the flat reflecting surface of the **reflectarray** can be surface mounted onto a building or a house wall and, thus, occupy an insignificant amount of real estate. Moreover, unlike conventional array antennas, the **reflectarray**, without any power divider, has very little ohmic insertion loss which helps the system's gain-over-temperature (G/T) performance when used as a receiving antenna"

The above fixed-beam microstrip array antennas are intended for a DBS system with a fixed ground terminal, such as a residential house. A DBS television receiving system is also applicable to mobile ground terminals, such as automobiles or trains. Toyota Central R&D Laboratories of Japan has recently developed a mechanically steered microstrip array for train applications. This antenna, shown in Figure 9, is a rectangular planar array that generates a fan beam with a wide beam in the elevation plane and a narrow beam in the azimuth plane. Therefore, mechanical steering in the azimuth plane is required to point its narrow beam at the satellite, while the train is moving about. This planar array[31] has 96 circular patch elements excited by an array of helices and fed by rectangular waveguides. It provides a minimum of 27.5 dBi gain at Ku-band frequency. The complete antenna system has a diameter of 60 cm and a height of 13 cm.

NASA/JPL and the U.S. Information Agency/Voice of America (USIA/VOA) are jointly developing a Direct Broadcast Satellite Radio (DBSR) system, which will provide audio services (AM,FM, etc.) to reach a variety of radio receivers (fixed, portable, and mobile) . The low-frequency audio signal is modulated onto a microwave frequency, i.e. , S-band, and transmitted to the users via the satellite. When successfully developed, it is expected that millions of radio receivers will be in demand by the general population. TWO types of microstrip antennas[32] have been studied for the DBSR system at the S-band frequency. One is the omnidirectional higher-order-mode circular patch[24] that was discussed earlier. It is intended as an outdoor low-gain antenna. The second one is a four-element medium-gain patch array shown in Figure 10. It provides circular polarization with 12 dBi of gain. The sequential rotation technique[11,12] is used to arrange the four elements to achieve good circular polarization over a relatively wide bandwidth. This four-element medium-gain patch array is intended as an indoor receiving antenna, and its extra gain, as compared with the outdoor low gain antenna, is used to compensate the RF loss that is incurred through the building structures.

VI. Nonsatellite-Based Applications

In addition to applications for satellite communications discussed in the previous sections, the microstrip antenna has also been found to be useful in many other areas. Because of its conformal mounting capability, microstrip antennas have been implemented on commercial aircraft for the purposes of altimetry, collision avoidance, remote sensing, etc. Small-size microstrip arrays have also been developed for the automobile collision avoidance system[33] at millimeter frequencies, as well as for the microwave sensing-alarm system. The medical hyperthermia application is another exciting area in which the microstrip antenna has been found to be useful . Among these nonsatellite-based applications, two important 'areas, remote sensing and medical hyperthermia, are selected for further discussion in the following paragraphs.

In the area of remote sensing, the Synthetic Aperture Radar (SAR) technique has been used to determine ground soil grades, vegetation type, ocean wave speed and direction, etc. , and has significant commercial impact on the general population in terms of agriculture and weather prediction. For example, a C-band interferometric SAR[34], recently developed by NASA/JPL, has successfully measured the characteristics of the ocean waves, which contributed to the prediction of weather. A McDonnell Douglas DC-8 aircraft has been used as the radar platform. Two identical microstrip arrays, separated by a prescribed distance to properly perform the interferometric function, are flush mounted on one side of the DC-8 fuselage. Each array [16] has a rectangular aperture and generates a fan-shaped beam in the broadside direction. A photograph of the microstrip array, in Figure 11., shows the two rows of square microstrip patches with a total of 76 elements. These two rows are excited with opposite phases to achieve the required low cross polarization. The relatively large number of elements are fed serially to minimize insertion loss and, thus, to achieve good efficiency. This array has achieved less than -30 dB of cross polarization in the main beam region and an overall efficiency of 72% with a peak gain of 23.8 dBi.

In the medical area, microwave energy has been found to be one of the most effective forms of inducing hyperthermia in treating malignant tumors. Difficulties have been experienced in heating deep-lying tissues and heating a relatively large volume of tissue. In general, the desired characteristics of a microwave applicator include an effective deposition of the energy in a defined tissue volume, good impedance matching, and conformality to the surface being treated so that minimum leakage of microwave energy will occur outside of the treated area. In addition, the radiator should be lightweight, rugged, and have an easy-to-handle design. The microstrip patch radiator seems to have met all these requirements. The early designs of microstrip radiators for hyperthermia applications were printed dipoles[35] and an annular ring[36] at an S-band frequency. A more recent design involves the use of a circular microstrip disk [37] at an L-band frequency. Two coupled microstrip lines with adjustable separation [38] have been used at a UHF frequency to measure the temperature gradient inside the human body. An interesting and unique application of the microstrip radiator is the flexible patch applicator [39] at 43o MHz. Figure 12 shows how the flexible microstrip patch can be applied to a curved surface for maximum efficiency.

VII. Conclusion

In the past decade, because of its low profile, small size, and low manufacturing cost, the microstrip antenna has been found to be in significant demand for commercial applications. Especially in the area of satellite communications, the demand for microstrip antennas is most evident. In other areas, such as remote sensing, medical usage, automobile collision avoidance, and aircraft systems, the microstrip antenna has also found important applications. Research and development in the microstrip antenna area should be continued to improve performance parameters, such as the bandwidth and insertion loss. It is believed that this small size antenna will continue to benefit the human race for many future years.

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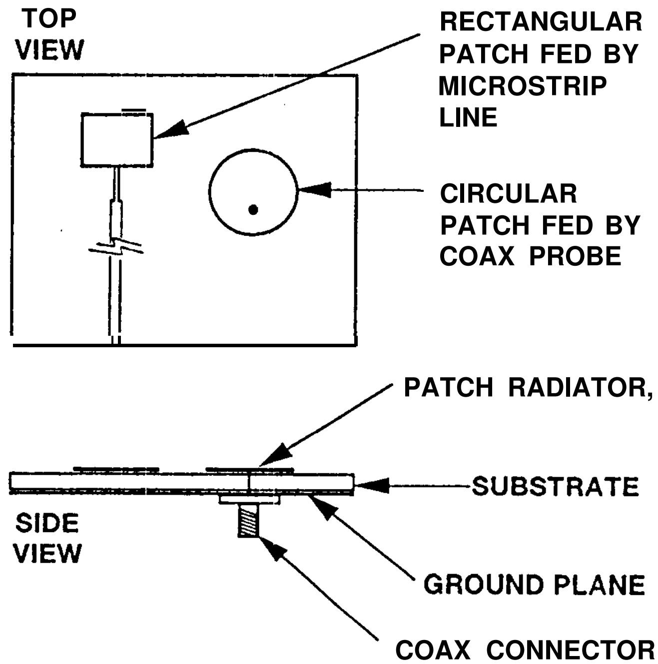
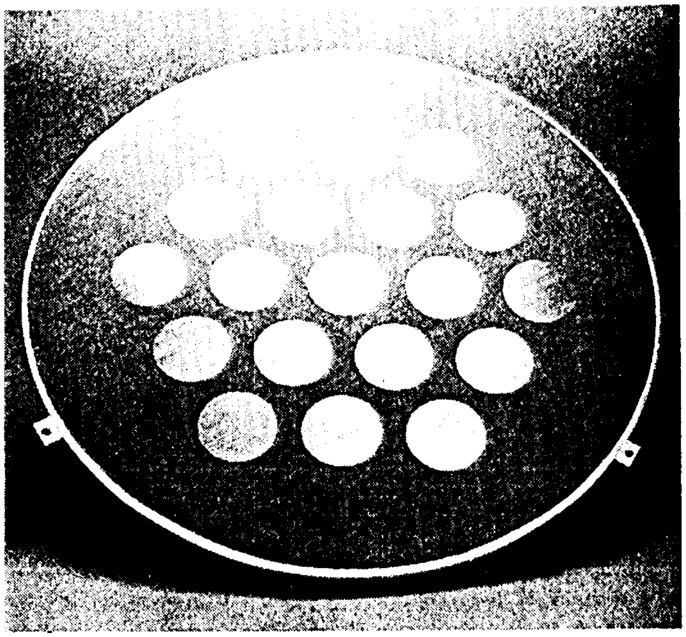


Figure 1. Rectangular and circular microstrip patch antenna configurations.



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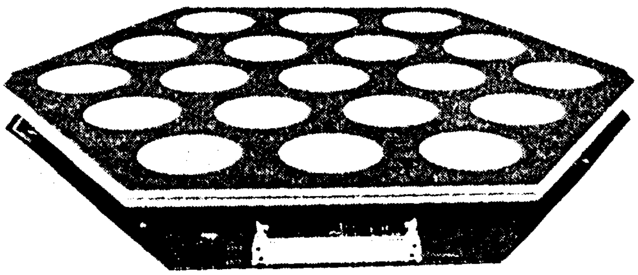

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Figure 2. Phased array antennas for mobile satellite communications.

Figure **3**. Phased array installed on a passenger car. (Courtesy of the Toyota Central **R** & D Labs)

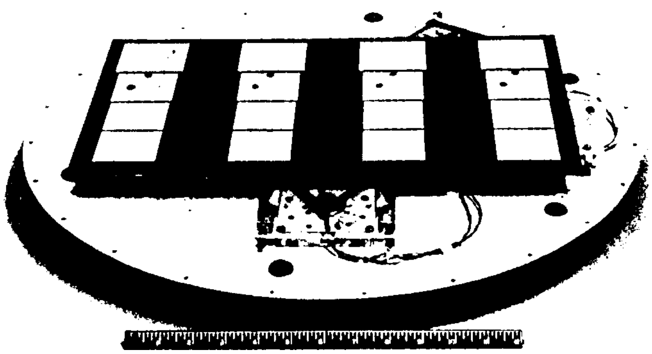
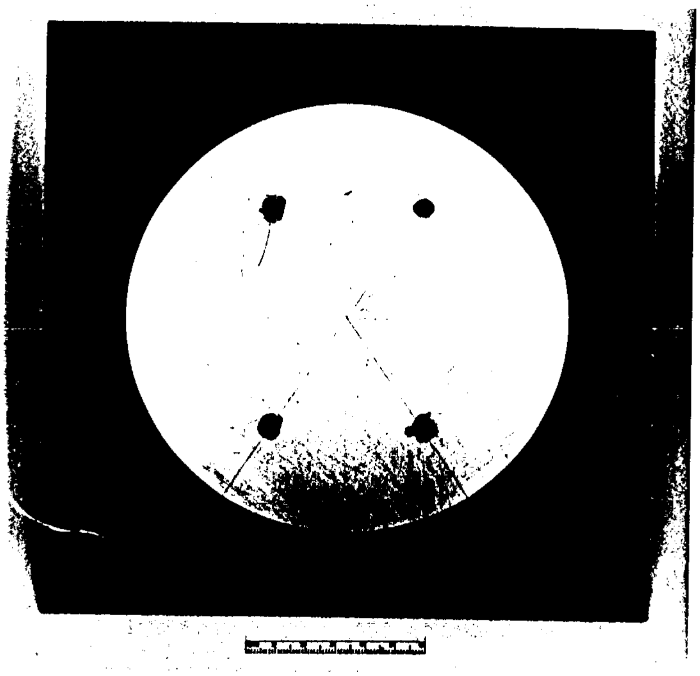
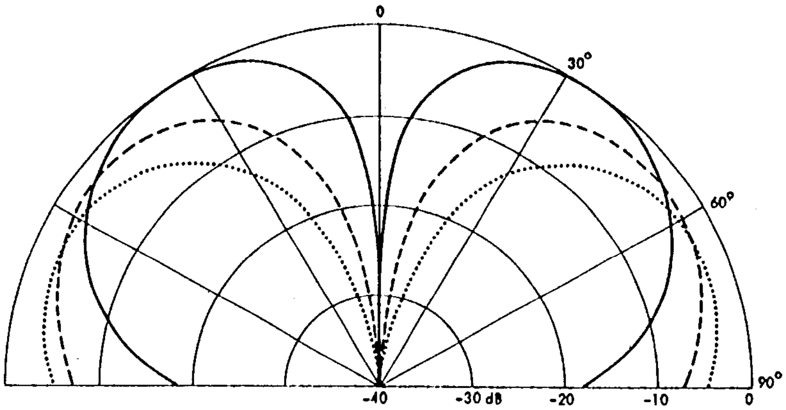


Figure 4. Mechanically steered low-profile **microstrip** Yagi array for mobile satellite communications.





	MODE	RELATIVE DIELECTRIC CONSTANT	PEAK DIRECTIVITY	PEAK DIRECTION FROM ZENITH	RADIATOR DIAMETER
———————	TM_{21}	1.25	6.9 dBi	35°	$0.9\lambda_0$
- - - - - -	TM_{31}	2.2	4.6	54°	0.93
···············	TM_{41}	4.2	4.0	69°	0.88

Figure 5. Higher-order-mode circularly polarized microstrip antenna. Photo shows the S-band 4th order mode patch.

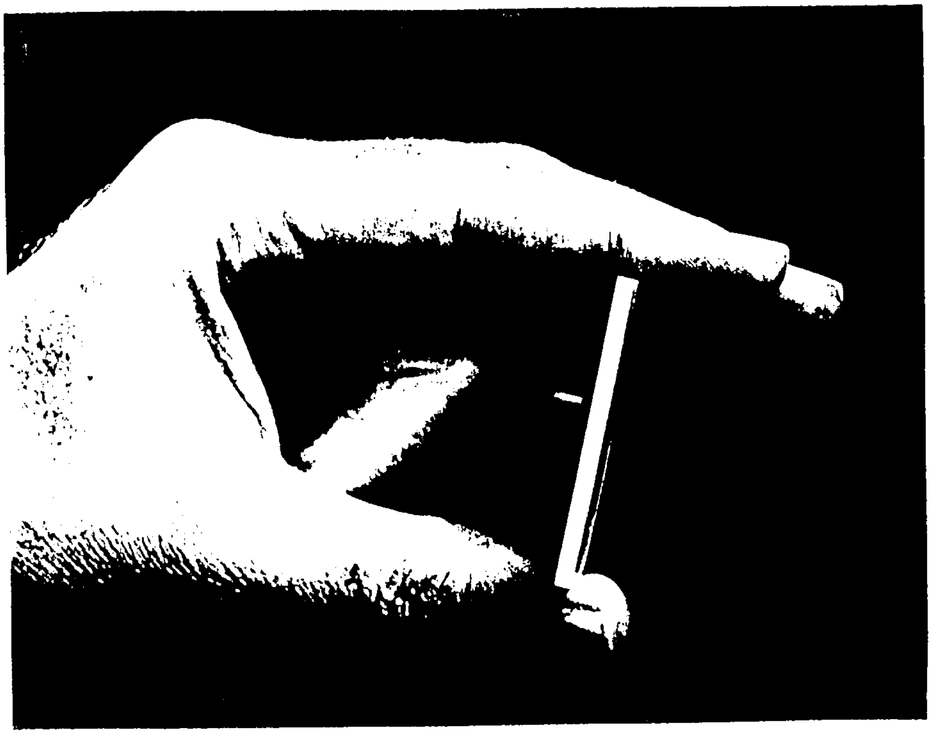


Figure 6. Microstrip patch antenna for GPS application.
(Courtesy of the Ball Corporation)

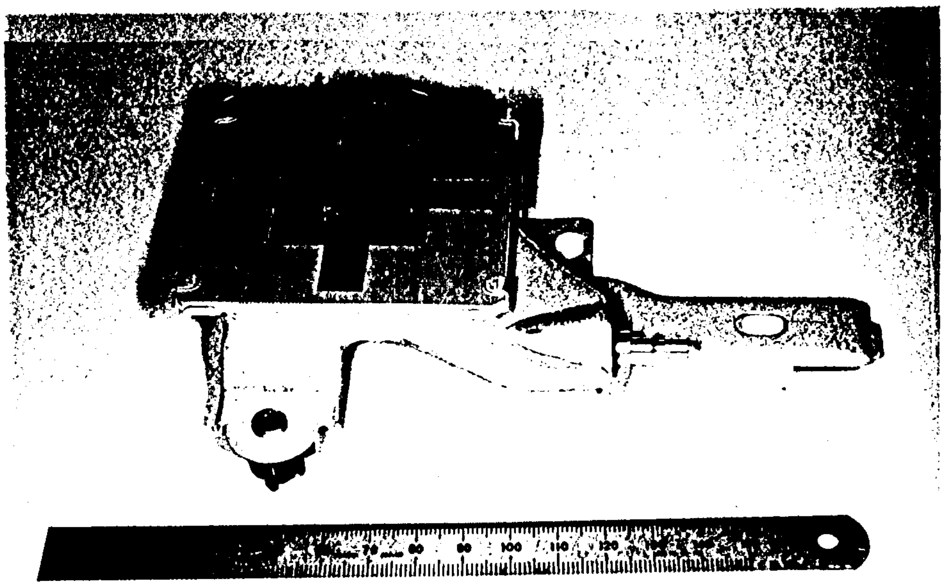


Figure 7. Microstrip patch antenna for GPS application.
(Courtesy of the Toyota Central R & D Labs)

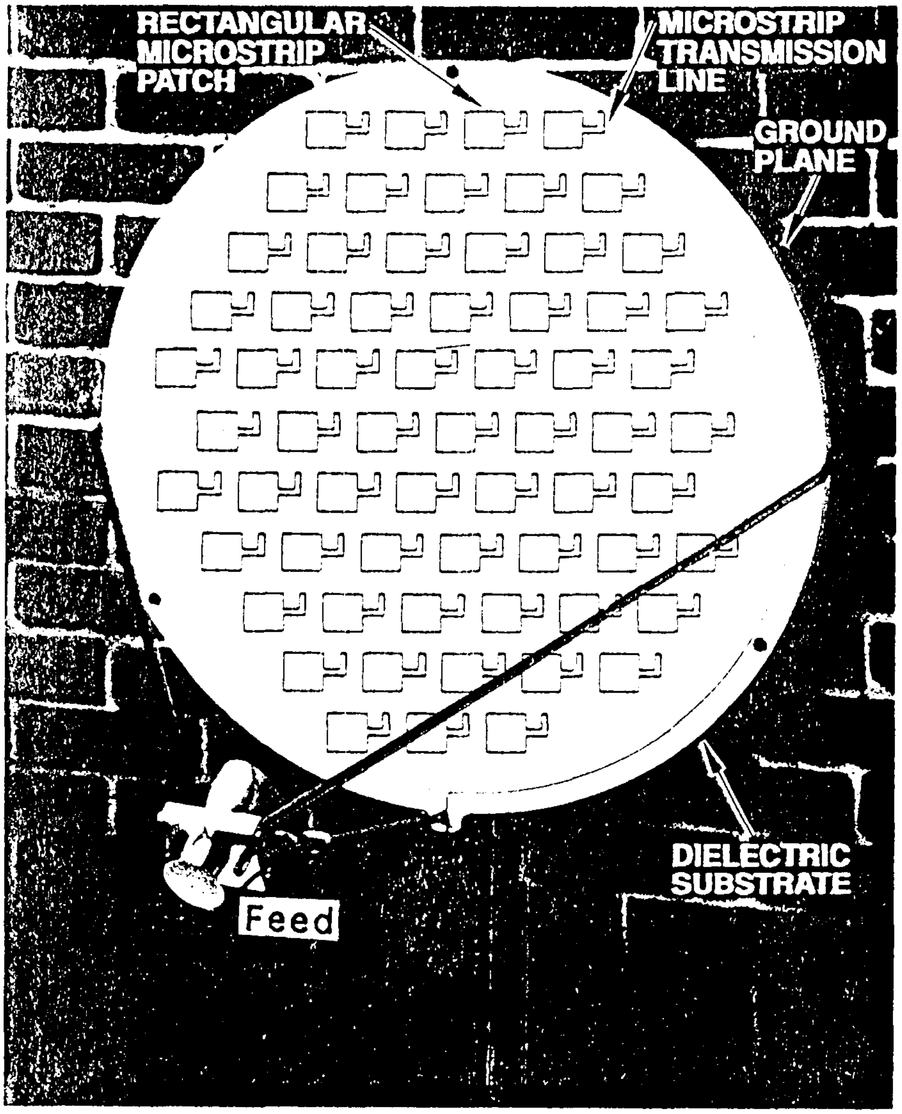


Figure 8. Microstrip reflectarray surface-mounted on building's wall for DBS application.

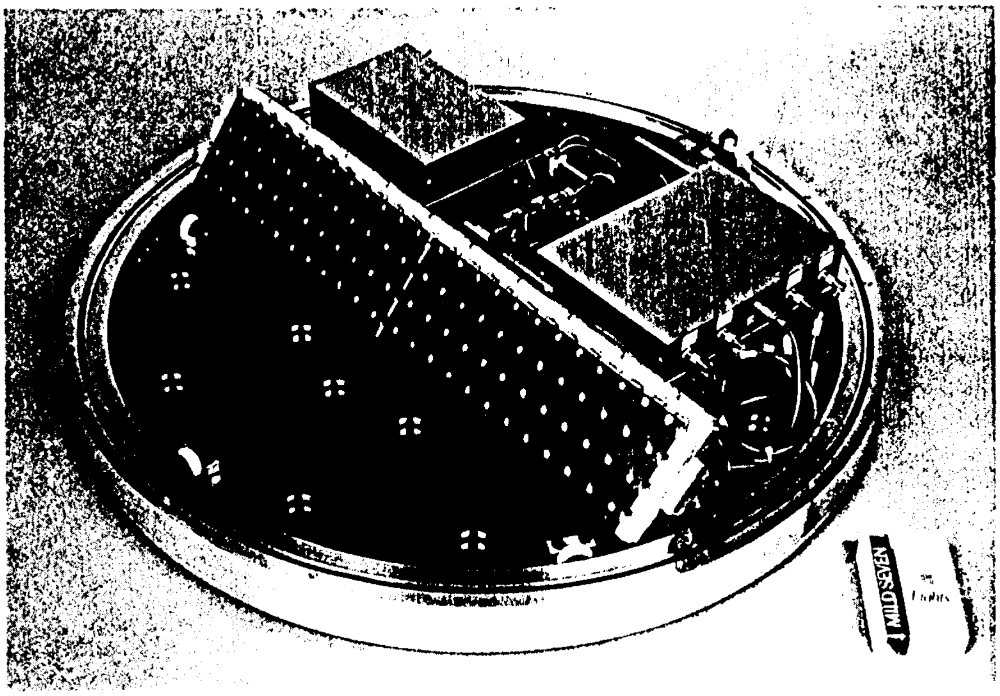


Figure 9. Mechanically steered microstrip array antenna for mounting on trains for DBS application [31].

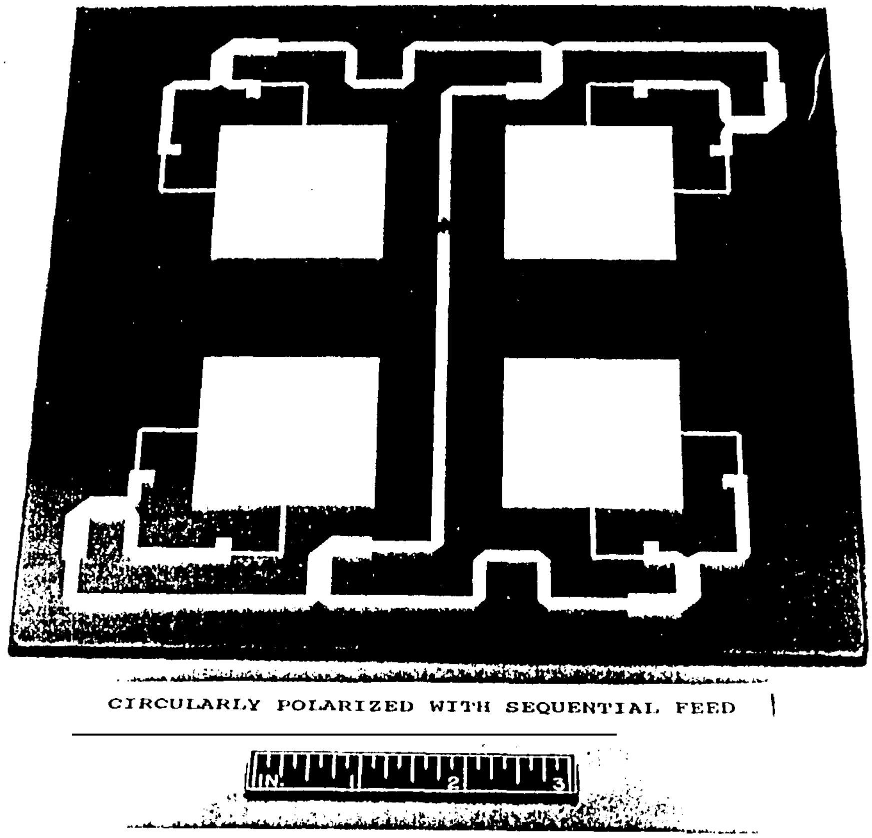


Figure 1.0. S-band **microstrip** array with briefcase size for Direct Broadcast Satellite Radio **(DBSR)** service.

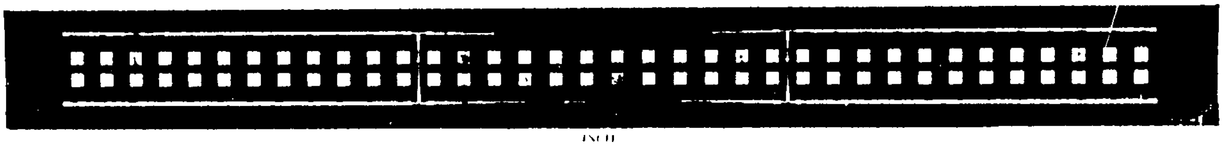


Figure 11. **Microstrip** array for aircraft **interferometric** radar remote sensing application.

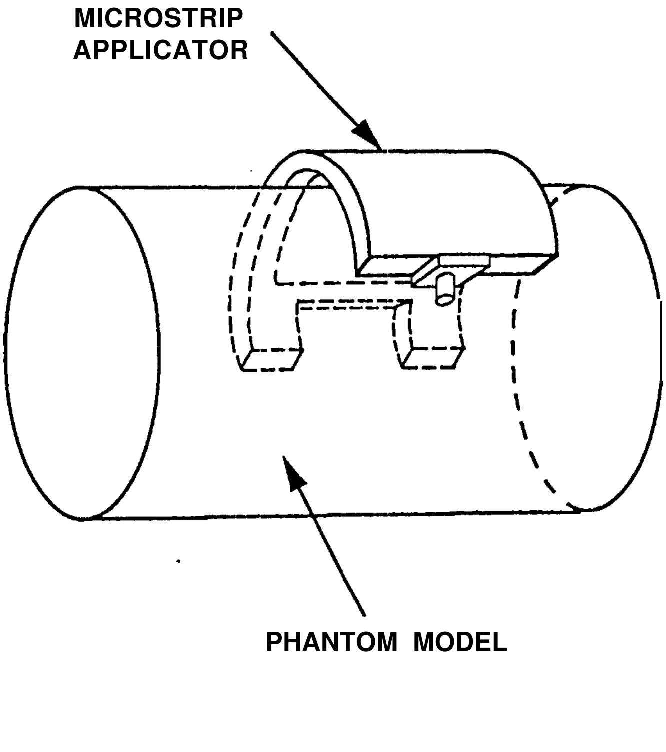


Figure 12. Flexible microstrip patch mounted on a curved surface for hyperthermia medical application [39].