A Review of Aperture Coupled Microstrip Antennas: History, Operation, Development, and Applications

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INTRODUCTION:

This article reviews the current status of aperture coupled microstrip antennas. Since its introduction in 1985 [1], the features offered by this antenna element have proved to be useful in a wide variety of applications, and the versatility and flexibility of the basic design have led to an extensive amount of development and design variations by workers throughout the world. We begin with some historical notes about the early development of this antenna, and discuss its main features relative to other types of microstrip antenna feeding methods. We then discuss the basic operating principles of the aperture coupled antenna, followed by a summary of the extensive development that this antenna has undergone, in terms of both practical design features and modeling techniques. We close with a short list of some of the applications of this antenna element.

To place this discussion in the larger context of microstrip antenna technology, we refer the reader to several articles that review this subject [2]-[5]. Some of the useful features and recent developments related to aperture coupled microstrip antennas are listed below:

- demonstrated impedance bandwidths ranging from 5% to 50%
- independent selection of antenna and feed substrate materials
- two-layer construction shields radiating aperture from feed network
- increased substrate space for antenna elements and feed lines
- convenient integration for active arrays
- theoretically zero cross polarization in principle planes
- many possible variations in patch shape, aperture shape, feed line type, radomes, etc.
- extension to aperture coupled microstrip line couplers, waveguide transitions, dielectric resonators, etc

HISTORY OF THE APERTURE COUPLED MICROSTRIP ANTENNA:

As discussed in more detail in [2]-[5], the rapid development of microstrip antenna technology began in the late 1970s. By the early 1980s basic microstrip antenna elements and arrays were fairly well established in terms of design and modeling, and workers were turning their attentions to improving antenna performance features (e.g., bandwidth), and to the increased application of the technology. One of these applications involved the use of microstrip antennas for integrated phased array systems, as the printed technology of microstrip antenna seemed perfectly suited to low-cost and high-density integration with active MIC or MMIC phase shifter and T/R circuitry. Our group at the University of Massachusetts (Dan Schaubert, Bob Jackson, Sigfrid Yngvesson, and this author) had received an Air Force contract to study this problem, in terms of design tradeoffs for various integrated phased array architectures, as well as theoretical modeling of large printed phased array antennas. The straightforward approach of building an integrated millimeter wave array (or subarray) using a single GaAs substrate layer had several drawbacks. First, there is generally not enough space on a single layer to hold antenna elements, active phase shifter and amplifier circuitry, bias lines, and RF feed lines. Second, the high permittivity of a semiconductor substrate such as GaAs was a poor choice for antenna bandwidth, since the bandwidth of a microstrip antenna is best for low dielectric constant substrates. And if substrate thickness is increased in an attempt to improve bandwidth, spurious feed radiation increases and surface wave power increases. This latter problem ultimately leads to scan blindness, whereby the antenna is unable to receive or transmit at a particular scan angle. Because of these and other issues, we were looking at the use of a variety of two or more layered substrates. One obvious possibility was to use two back-to-back substrates with feed through pins. This would allow plenty of surface area, and had the critical advantage of allowing the use of GaAs (or similar) material for one substrate, with a low dielectric constant for the antenna elements. The main problem with this approach was that the large number of via holes presented fabrication problems in terms of yield and reliability. We had looked at the possibility of using a two sided-substrate with printed slot antennas fed with microstrip lines [6], but the bidirectionality of the radiating element was unacceptable. At some point in the summer of 1984 we arrived at the idea of combining these two geometries, using a slot or aperture to couple a microstrip feed line to a resonant microstrip patch antenna.

After considering the application of small hole coupling theory to the fields of the microstrip line and the microstrip antenna, we designed a prototype element for testing. Our intuitive theory was very simple, but good enough to suggest that maximum coupling would occur when the feed line was centered across the aperture, with the aperture positioned below the center of the patch, and oriented to excite the magnetic field of the patch. The first aperture coupled microstrip antenna was fabricated and tested by a graduate student, Allen Buck, on August 1, 1984, in the University of Massachusetts Antenna Lab. This antenna used 0.062" Duroid substrates with a circular coupling aperture, and operated at 2 GHz [1]. As is the case with most original antenna developments, the prototype element was designed without any rigorous analysis or CAD - only an intuitive view of how the fields might possibly couple through a small aperture. We were pleasantly surprised to find that this first prototype worked almost perfectly - it was impedance matched, and the radiation patterns were good. Most importantly, the required coupling aperture was small enough so that the back radiation from the coupling aperture was much smaller than the forward radiation level.

BASIC OPERATION OF THE APERTURE COUPLED MICROSTRIP ANTENNA:

Figure 1 shows the geometry of the basic aperture coupled patch antenna. The radiating microstrip patch element is etched on the top of the antenna substrate, and the microstrip feed line is etched on the bottom of the feed substrate. The thickness and dielectric constants of these two substrates may thus be chosen independently to optimize the distinct electrical functions of radiation and circuitry. Although the original prototype antenna used a circular coupling aperture, it was quickly realized that the use of a rectangular slot would improve the coupling, for a given aperture area, due to its increased magnetic polarizability [1]. Most aperture coupled microstrip antennas now use rectangular slots, or variations thereof. The aperture coupled microstrip antenna involves over a dozen material and dimensional parameters, and we summarize the basic trends with variation of these parameters below:

antenna substrate dielectric constant:
This primarily affects the bandwidth and radiation efficiency of the antenna, with lower permittivity giving wider impedance bandwidth and reduced surface wave excitation.

antenna substrate thickness:
Substrate thickness affects bandwidth and coupling level. A thicker substrate results in wider bandwidth, but less coupling for a given aperture size.

microstrip patch length:
The length of the patch radiator determines the resonant frequency of the antenna.

microstrip patch width:
The width of the patch affects the resonant resistance of the antenna, with a wider patch giving a lower resistance. Square patches may result in the generation of high cross polarization levels, and thus should be avoided unless dual or circular polarization is required.

feed substrate dielectric constant:
This should be selected for good microstrip circuit qualities, typically in the range of 2 to 10.

feed substrate thickness:
Thinner microstrip substrates result in less spurious radiation from feed lines, but higher loss. A compromise of 0.01λ to 0.02λ is usually good.

slot length:
The coupling level is primarily determined by the length of the coupling slot, as well as the back radiation level. The slot should therefore be made no larger than is required for impedance matching.

slot width:
The width of the slot als affects the coupling level, but to a much less degree than the slot width. The ratio of slot length to width is typically 1/10.

feed line width:
Besides controlling the characteristic impedance of the feed line, the width of the feed line affects the coupling to the slot. To a certain degree, thinner feed lines couple more strongly to the slot.

feed line position relative to slot:
For maximum coupling, the feed line should be positioned at right angles to the center of the slot. Skewing the feed line from the slot will reduce the coupling, as will positioning the feed line towards the edge of the slot.

position of the patch relative to the slot:
For maximum coupling, the patch should be centered over the slot. Moving the patch relative to the slot in the H-plane direction has little effect, while moving the patch relative to the slot in the E-plane (resonant) direction will decrease the coupling level.

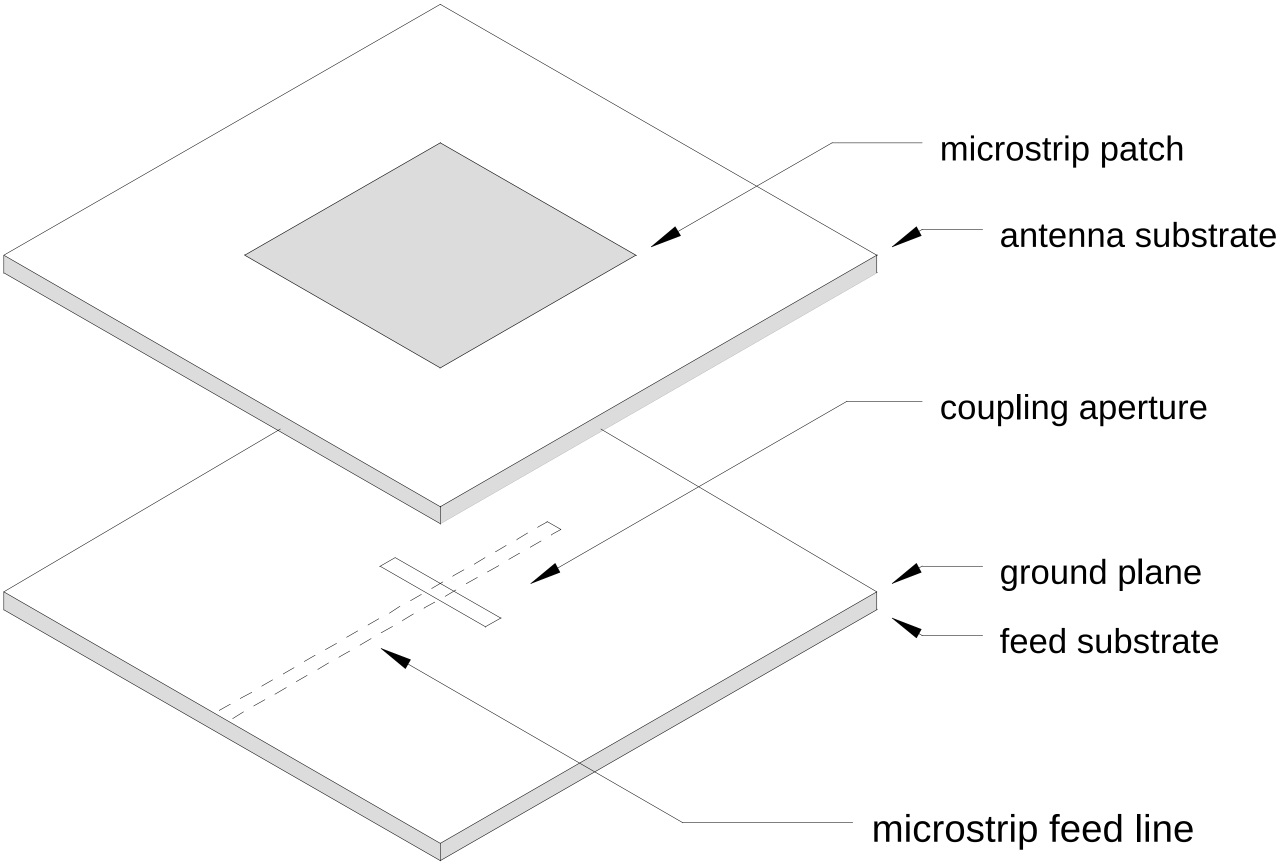

Figure 1. Geometry of the basic aperture coupled microstrip antenna.

length of tuning stub:
The tuning stub is used to tune the excess reactance of the slot coupled antenna. The stub is typically slightly less than $\lambda g/4$ in length; shortening the stub will move the impedance locus in the capacitive direction on the Smith chart.

Figure 2 shows a typical Smith chart plot of the impedance locus versus frequency for an aperture coupled microstrip antenna. The size of the locus is controlled primarily by the slot length; increasing the slot length increases the diameter of the circular portion of the locus. The effect of the stub length is to rotate the entire locus up (inductive) or down (capacitive) on the chart. Thus, optimum matching, where the locus is just large enough to pass through the center of the Smith chart, can be obtained by properly adjusting the slot length and the stub length.

Figure 3 shows a typical radiation pattern plot for an aperture coupled microstrip antenna. The forward radiation patterns are typical of those obtained with microstrip antenna elements, while the back radiation lobe is caused by radiation from the coupling slot.

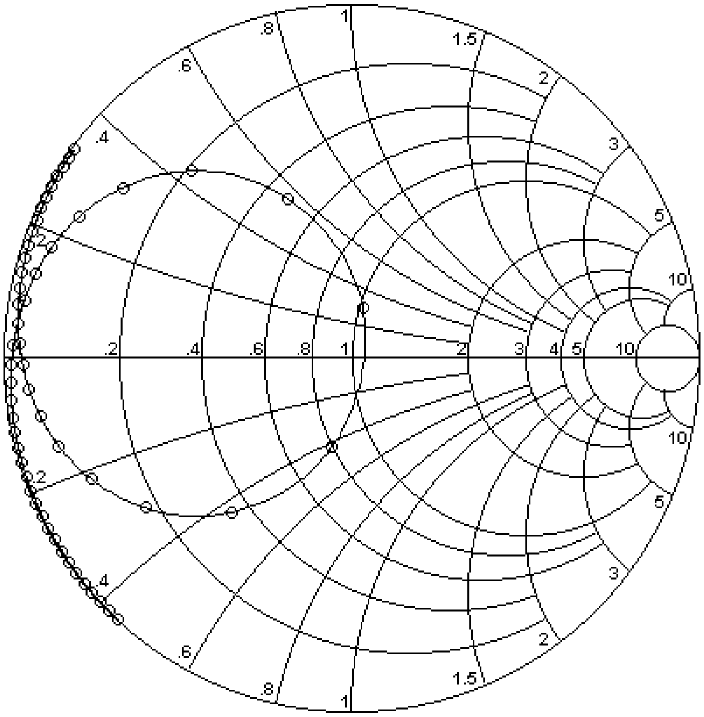

Figure 2. Smith chart plot of the impedance locus versus frequency for an aperture coupled microstrip antenna.

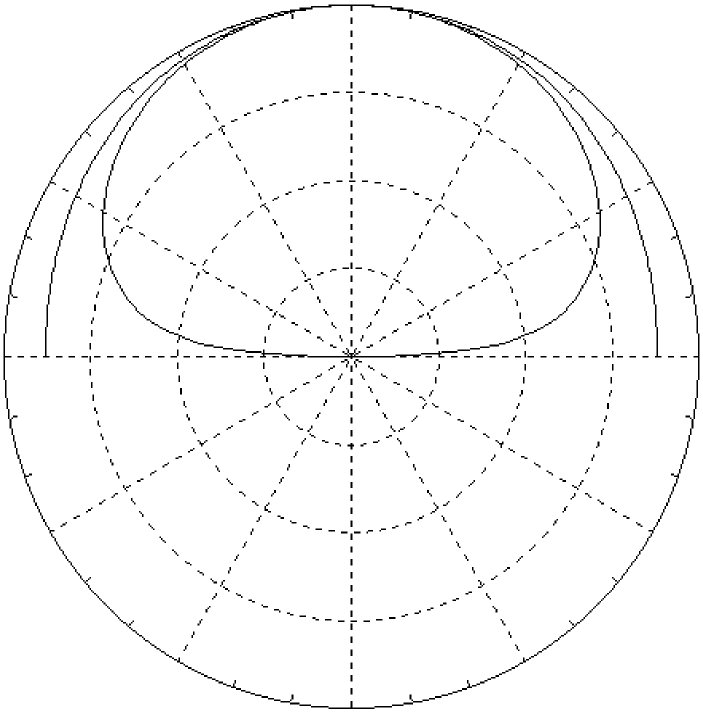

Figure 3. Principal plane patterns for an aperture coupled microstrip antenna.

VARIATIONS ON THE APERTURE COUPLED MICROSTRIP ANTENNA:

Since the first aperture coupled microstrip antenna was proposed, a large number of variations in geometry have been suggested by workers around the world. The fact that the aperture coupled antenna geometry lends itself so well to such modifications is due in part to the nature of printed antenna technology itself, but also to the multi-layer structure of the antenna. Below we categorize some of the modifed designs that have evolved from the basic aperture coupled antenna geometry:

radiating elements:

The original aperture coupled antenna used a single rectangular patch. Since then, workers have successfully demonstrated the use of circular patches, stacked patches, parasitically coupled patches, patches with loading slots, and radiating elements consisting of multiple thin printed dipoles. Most of these modifications are intended to yield improved bandwidth, and this topic is discussed in more detail in the following section.

slot shape:

The shape of the coupling aperture has a significant impact on the strength of coupling between the feed line and patch. Thin rectangular coupling slots have been used in the majority of aperture coupled microstrip antennas, as these give better coupling than round apertures. Slots with enlarged ends, such as “dogbone”, bow-tie, or H-shaped apertures can further improve coupling.

type of feed line:

The microstrip feed line can be replaced with other planar lines, such as stripline, coplanar waveguide, dielectric waveguide, and similar. The coupling level may be reduced with such lines, however. It is also possible to invert the feed substrate, inserting an additional dielectric layer so that the feed line is between the ground plane and the patch element.

polarization:

Besides linear polarization, it has been demonstrated that dual polarization and circular polarization can be obtained with aperture coupled elements. This is discussed in more detail in the following section.

dielectric layers:

As with other types of microstrip antennas, it is easy to add a radome layer to an aperture coupled antenna, either directly over the radiating element, or spaced above the element. It is also possible to form the antenna and feed substrates from multiple layers, such as foam with thin dielectric skins for the etched conductors.

LATER DEVELOPMENT OF THE APERTURE COUPLED MICROSTRIP ANTENNA:

Here we discuss in more detail, and with references, some of the significant developments in the field of aperture coupled microstrip antennas.

Wideband aperture coupled microstrip antennas

One of the useful features of the aperture coupled microstrip antenna is that it can provide substantially improved impedance bandwidths. While single layer probe or microstrip line-fed elements are typically limited to bandwidths of 2%-5%, aperture coupled elements have been demonstrated with bandwidths up to 10 - 15% with a single layer [7]-[9], and up to 30-50% with a stacked patch configuration [10]-[13]. This improvement in bandwidth is primarily a result of the additional degrees of freedom offered by the stub length and coupling aperture size. The tuning stub length can be adjusted to offset the inductive shift in impedance that generally occurs when thick antenna substrates are used, and the slot can be brought close to resonance to achieve a double tuning effect. Use of a stacked patch configuration also introduces a double tuning effect.

Dual and circularly polarized aperture coupled microstrip antennas

As with other types of microstrip antennas, dual polarization capability can be obtained by using two orthogonal feeds. This was first demonstrated by Adrian and Schaubert [14], with two orthogonal non-overlapping slots were used to feed a square patch element. Dual linear polarization with 18 dB isolation was achieved, and circular polarization was demonstrated using an off-board 90° hybrid coupler. One problem with this approach was that the asymmetry of the slots constrained the size of the slots (and thus the coupling level that could be achieved), and also limited the isolation and polarization purity. Another approach was suggested by Tsao, Hwang, Killburg, and Dietrich, whereby a crossed slot was used to feed the patch [15]. In this case 27 dB isolation was achieved, with very good bandwidth. The drawback in this case was the requirement for a crossover in the balanced feed lines that fed each arm of the crossed slot. This problem was solved by Targonski and Pozar [8], who used a different arrangement of feed lines with the crossed slot for circular polarization. This element led to a 3 dB axial ratio bandwidth of up to 50%, and a comparable impedance bandwidth. It is also possible to use a crossed slot feed with two feed lines on distinct substrate layers to avoid the crossover problem, as demonstrated in [16]. Circularly polarized aperture coupled elements can also be designed with a single diagonal coupling slot and a slightly non-square patch [17], similar to circularly polarized patches with a single probe feed, but the resulting axial ratio bandwidth is very narrow. Somewhat improved axial ratio bandwidth can be obtained by using a crossed slot with a single microstrip feed line through the diagonal of the cross, and a slightly non-square patch [18].

Aperture coupled microstrip antenna arrays

Like other types of microstrip antennas, aperture coupled elements lend themselves well to arrays using either series or corporate feed networks. The two-sided structure of the aperture coupled element allows plenty of space for feed network layout, and this extra room is especially useful for dual-polarized or dual frequency arrays. In addition, the ground plane serves as a very effective shield between the radiating aperture and the feed network. One drawback is that the coupling apertures will radiate a small amount of power in the back direction, but in practice a ground plane located some distance below the feed layer can be used to eliminate this radiation. Some examples of corporate-fed aperture coupled array antennas are given in references [4],[7] and [12]. In addition, series fed aperture coupled arrays have been demonstrated, as in [19].

Monolithic arrays using aperture coupled microstrip antennas

While the objective of a truly monolithic array with integrated planar antennas and phase shifters was largely the driving force behind the development of the aperture coupled microstrip element, there are only a few examples where such arrays have actually been implemented.

One of the first monolithically integrated antennas was the 40 GHz module reported by Ohmine, Kashiwa, Ishikawa, Iida, and Matsunaga [20]. In this work, an aperture coupled antenna element was integrated with a three-stage RF amplifier and a mixer. Probably the best example of a fully integrated phased array is the 4x4 Ka-band subarray developed by Texas Instruments [21]. This antenna used circular aperture coupled patch elements, with 16 4-bit MMIC phase shifters and 16 100mW MMIC power amplifiers. This work successfully demonstrated beam scanning up to 45°, with an ERP of 77 watts at 30 GHz.

Modeling of aperture coupled microstrip antennas

Analysis of the aperture coupled microstrip element is complicated by the presence of two dielectric layers, and the microstrip line-to-slot transition. In fact, however, the slot feed is generally easier to model in a rigorous manner than a probe or line-fed element because the patch current near the feed point is less singular. The initial report of the aperture coupled element [1] presented only a simplified cavity-type model, and the antenna was not rigorously analyzed until Sullivan and Schaubert [22] treated it using a full-wave moment method solution. This work also presented data showing the effect of various design parameters, such as slot position and size, on the input impedance locus of the antenna. An alternative way of treating the microstrip to slot transition was introduced by Pozar [23]. This technique was derived using the reciprocity theorem, and eliminates the need for brute-force modeling of the microstrip feed line and stub. Many later analyses, both moment method and cavity model, utilized this technique for treating the feed. The moment method technique has also been applied to mutual coupling between aperture coupled elements [24], and to infinite arrays of aperture coupled elements [25].

Moment method analysis techniques are rigorous, highly accurate, and versatile enough to handle important practical variations such as stacked patches, patches with radome layers, and patches fed with stripline, but at the expense of relatively long computer run times. Cavity models, on the other hand, are more approximate, but require neglible computer resources. Some examples of cavity models for aperture coupled microstrip antennas include [26]-[27].

Computer aided design software for aperture coupled microstrip antennas

Computer aided design (CAD) software is one of the most pervasive subjects in the fields of microwave and antenna engineering today, probably because of the perception among engineers that such software will not only make their work easier but provide a tool solve problems that would not otherwise be possible. CAD software has reached a fairly high level of refinement in areas such as the analysis of low-frequency circuits, and the analysis and optimization of passive and active microwave circuits. With these software products, user confidence is high and prototype designs can be manufactured with an acceptable level of trial-and-error adjustment, if necessary. CAD software for microstrip antennas, however, lags far behind, often committing the designer to costly experimental iterations, sometimes even for a single radiating element.

At the present time there are two commercially available CAD software packages written specifically for aperture coupled microstrip antennas. PCAAD 3.0 is a Windows-based general purpose antenna analysis and design tool written by the author (url reference). PCAAD 3.0 can treat several types of antennas and arrays, and includes a cavity model solution for the basic aperture coupled antenna element. A more rigorous solution is available with ENSEMBLE 2.0 (url reference), which implements a general moment method solution capable of handling arbitrarily shaped patches, coupling apertures, and feed networks.

APPLICATIONS OF APERTURE COUPLED MICROSTRIP ANTENNAS:

While most of the rapid advances in microstrip antennas and arrays that took place in the 1980s were driven by defense and space markets [2] present applications of this technology are growing most rapidly in the commercial sector. While specifications for defense and space application antennas typically emphasize maximum performance with little constraint on cost, commercial applications demand low cost components, often at the expense of reduced electrical performance. Thus, microstrip antennas for commercial systems require low-cost materials, and simple and inexpensive fabrication techniques. Some of the commercial systems that presently use microstrip antennas are listed in the table below:

Application	**Frequency**
Global Positioning Satellite	1575 MHz and 1227 MHz
Paging	931-932 MHz
Cellular Phone	824-849 MHz and 869-895 MHz
Personal Communication System	1.85-1.99 GHz and 2.18-2.20 GHz
GSM	890-915 MHz and 935-960 MHz
Wireless Local Area Networks	2.40-2.48 GHz and 5.4 GHz
Cellular Video	28 GHz
Direct Broadcast Satellite	11.7-12.5 GHz
Automatic Toll Collection	905 MHz and 5-6 GHz
Collision Avoidance Radar	60 GHz, 77 GHz, and 94 GHz
Wide Area Computer Networks	60 GHz

Most of these applications involve sales in excess of 10,000 units per month. For example, WLAN sales in the US was $57M in 1993, and is projected to exceed $900M by 1998. In 1994 there were 11 million cellular phone users in the Asia-Pacific Rim region; this number is expected to increase to 78 million by the year 2000. The number of DBS installations worldwide is expected to reach 30 million by the year 2000. Similar growth rates are expected for paging, RF identification systems (RFID), and mobile data systems. In addition, several major worldwide satellite communication systems are either in progress or being planned, including the 66 satellite IRIDIUM program, MSAT, GLOBALSTAR, AMSC, and the proposed millimeter wave Teledesics satellite system. Overall, the market for antennas is expected to grow more than 35% annually from 1995 to 2000, with sales increasing from $400M to $2B over that period. Most of this revenue will be for high-volume low-cost antennas, with little funding for advanced research and development.

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