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A Study of 60 Gigahertz Intersatellite Link Applications

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A STUDY OF 60 GHz INTERSATELLITE LINK APPLICATIONS

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ABSTRACT

Applications of intersatellite links (ISLs) operating at 60 GHz are reviewed. Likely scenarios, ranging from transmission of moderate and high data rates over long distances to low data rates over short distances are examined. A limited parametric tradeoff is performed with system variables such as radiofrequency power, receiver noise temperature, link distance, data rate, and antenna size. Present status is discussed and projections are given for both electron tube and solid state transmitter technologies. Monolithic transmit and receive module technology, already under development at 20 and 30 GHz, is reviewed and its extension to 60 GHz, and possible applicability is discussed.

INTRODUCTION

Approximately 9 GHz of bandwidth, in the neighborhood of 60 GHz, are presently allocated for intersatellite link (ISL) applications. Compared to lower frequency links, 60 GHz offers reasonable antenna size, large available bandwidth, and a degree of freedom from terrestrially based eavesdropping and interference.

Of course, optical link technology shares all of these potential advantages in even greater degree. However, optical link technology, appropriate for space use, has formidable acquisition and pointing problems between moving platforms and is presently expected to be heavier and more expensive than corresponding 60 GHz technology (ref. 1). Accordingly, it is expected that 60 GHz intersatellite links will have a significant role in future satellite communication applications, notwithstanding the impressive potential capabilities for optical ISLs.

To date, the applications of ISLs have been primarily experimental, involving relatively short distances and low data rates. NASA's Tracking and Data Relay Satellite System (TDRSS) will probably be the first operational application of an intersatellite link employing multiple satellites with high data rate links at microwave frequencies. Additional ISLs are certain to be utilized in the near future to ease the burden of ever growing data transmission requirements and provide operational flexibility.

HIGH DATA RATE ISL APPLICATION AND REQUIREMENTS

Likely applications of ISLs can be separated into three broad areas (ref. 2):

- o Communications (Domsats, Intelsats, etc.)
- o Data relay systems (earth resources, oceans, etc.)
- o Space research (TDRSS, space platform, etc.)

Recent advances in efficient microwave power generation by both traveling wave tubes (TWTs) (ref. 3) and solid state devices (IMPATT and Gunn diodes) are paving the way to implementation of millimeter wave ISLs in all of the above demanding applications. With the exception of one GHz of bandwidth allocated at 23 and 32 GHz (ref. 1), all bands assigned for ISL applications are above 50 GHz. The frequency bands from 54 to 58 GHz and 59 to 64 GHz, specifically designated for intersatellite service, are of interest because of very wide bandwidth, near term availability of adequate power sources and system components, and benefits associated with high atmospheric attenuation. Utilization of ISLs at frequencies below 50 GHz for international satellite traffic has already been considered and probably will be implemented in the near future by Intelsat (refs. 4-6).

Possible applications for 60 GHz intersatellite links include:

a. International links characterized by moderate data rates and large distances,

b. Cluster satellite concepts characterized by moderate data rates and short distances, and

c. Space platform and its diverse communication requirements ranging from low data rates over short distance to high data rates over long distances.

The objective of this study is to examine the applications of 60 GHz intersatellite links in various likely scenarios including low earth orbits (LEO) and geostationary orbits (GEO). A limited parametric tradeoff is performed with system variables such as radio-frequency power, receiver noise temperature, link distance, data rate, and antenna size. A simple heterodyne transponder, such as shown in Figure 1, is assumed for all ISL cases presented. The modulation used was quadriphase shift keying (QPSK). The transmitter powers shown for various ISLs do not include operation during solar conjunction. Assuming a receiving system temperature of 6000 degrees Kelvin (ref.7) at solar conjunction for ISLs with antenna diameters of 0.6 meters or greater, a power increase of approximately 8 dB over all links employing 1000 degree Kelvin receivers is required to prevent on outage. For links with antenna diameters less than 0.6 meters a smaller power increase, proportional to the ratio of the sun disk to antenna half power beamwidth is required.

International ISLs

A number of large commerce and population centers on earth are separated by distances that are too long to permit direct communications through a common geostationary satellite. In most such cases, the traffic is routed to a third country with a view of the satellite or a "double hop" is employed to effect the connection. An ISL appears to be an attractive alternative in such cases.

Figure 2 shows that a standard commercial communications channel of 274 megabits per second can be transmitted over very long distances with reasonable antenna sizes and power between 5 and 100 watts. Additional power reduction may be accomplished by optimization of parameters required for the specific link scenario as listed on the sample power budget in Table 1.

Cluster Satellite System ISLs

Special situations may require that a number of satellites be clustered in one area. The maximum distance between these satellites would be approximately 50 km. Intersatellite links may be desirable in these situations (ref. 8).

Figure 3 presents the permissible data rate versus clustered satellite distance for two antenna sizes and two receiver noise temperatures with one milliwatt of transmitter power. The application appears to be within reach of future monolithic integrated circuit technology.

Space Station ISL Application

NASA is presently involved in a planning exercise to determine the characteristics of low earth orbit space stations that would be affordable, use advanced technology currently under development, and capitalize on the space shuttle to enable a continuous U.S. presence in space for research, industrial, and satellite servicing applications. Intersatellite link applications associated with a space station would range from low to moderate data rates (approximately 100 kilobits per second to 100 megabits per second) between the space station and several free flyers in the vicinity (fig. 4) to high data rate (approximately 1 gigabit per second or more) between the space station and TDRSS (fig. 5). The first class of application would be characterized by only modest power requirements, but perhaps formidable pointing, acquisition, and antenna view angle and blockage problems. Distances would be typically much less than one degree of geostationary arc equivalent.

TECHNOLOGY STATUS AND PROJECTION

The transmitter technology at 60 GHz is advancing in both electron tube and solid state areas. Traveling wave tube amplifiers generally offer much higher efficiencies, bandwidth and power than solid state devices (fig. 6).

Traveling Wave Tubes

Recent innovations have led to impressive advances in the power and efficiency of traveling wave tubes. And for large bandwidth, long distance links (fig. 2) only traveling wave tubes have the potential capability of providing adequate power. If the system must be designed to operate through solar conjunction the class of applications for which only traveling wave tubes have adequate power is much broader. Traveling wave tubes, usable at 60 GHz can potentially employ three different slow wave structures: coupled cavity, ring-bar and the Tunneladder circuit.

A 50 GHz coupled cavity tube with 400 watts output power and 5 percent bandwidth was reported on in 1977 (ref. 9). Scaling the expected power by $(freq)^{-3}$ and derating the technology by a factor of 3, to allow for conservative space tube design, about 75 watts can be expected from coupled cavity technology at 60 GHz. NASA-Lewis has a program underway to develop a 75 watt, 60 GHz coupled cavity tube with a 3 GHz bandwidth and 40 percent efficiency (based on an optimized multistage depressed collector).

The ring-bar circuit (refs. 10-12) with diamond support rods, offers power comparable to that of the coupled cavity circuit but at a much larger bandwidth - perhaps 6 percent.

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A promising new TWT structure that is compatible with low cost fabrication techniques, is the so-called Tunneladder (ref. 13) circuit. NASA-Lewis currently has a program to develop a 40 GHz space tube, based on this circuit, with 200 watts of output power. Scaling the power as $(freq)^{-3}$, a reasonable expectation at 60 GHz would be 60 watts. The bandwidth expected for this circuit would be about one percent.

For all of the above circuits a realistic efficiency goal, based on an optimized multistage depressed collector, would be 40 percent. As indicated on Figure 6, the maximum efficiency for each type of TWT occurs at maximum power. Lower power tubes will have lower efficiency.

Solid State Transmitter Technology

Solid state transmitter technology is characterized by slow but steady progress both in single device and novel combiner efficiency and power.

At the present time, only IMPATT and Gunn diodes are available as solid state sources of appreciable amounts of 60 GHz power. As is widely known, Gunn diode oscillators are less noisy but IMPATT diodes are capable of substantially higher power. Thus, Gunn diodes are preferred for local oscillator applications, but IMPATTs are preferred for solid state transmitter application.

In order to provide radiofrequency power in excess of one watt, the output power from several IMPATT diodes must be combined in an external circuit. A 4 watt, 60 GHz, 2.5 GHz bandwidth amplifier is in the development phase by NASA GSFC (fig. 6-8). A wideband conical combiner is employed (fig. 8). Development of a 10 watt amplifier is planned for the near future.

As indicated by Figure 6, the overall efficiency goal is 4 percent. Figure 7 shows that the expected combining efficiency of the final high power stage is 89 percent. This illustrates the major problem with 60 GHz solid state transmitters for space application. The state-of-the-art in 60 GHz IMPATT diode efficiency is much less than 10 percent.

At present, the only mature 60 GHz IMPATT diode technology is based on silicon. Silicon IMPATTs with efficiency as high as 14 percent at 50 GHz, with reasonable junction temperature, have been produced in the laboratory (ref. 14). However, commercially available devices generally have power added efficiency in the 5-7 percent range. Accordingly, several organizations are pursuing the development of more efficient 60 GHz IMPATT diodes. The programs in this area (organizations, goals, and approaches) are identified in Table 2. Efficiency and power-per-device goals of 15% and 1 watt, respectively, determine the upper boundary of the solid state amplifier region in Figure 6.

The most prominent difficulty associated with the developments described in Table 2 is the stringent control over dopant density versus position that is required for high efficiency 60 GHz IMPATT profiles. This requirement is illustrated by Figure 9 which shows a hybrid-double drift Read profile that is typical of the high efficiency gallium arsenide (GaAs) approaches identified in Table 2. Both n and p regions have transitions that must be controlled (in location and sharpness) within a few hundred angstroms.

Only two growth technologies are thought to be capable of the required control and both are currently used only for research. Molecular beam epitaxy (MBE) is the front runner for achieving the required control of material characteristics. But MBE is a high vacuum technique with high cost, low throughput, and long turn around time. However, for the production of small volumes of high cost, high performance, space devices, MBE would be acceptable. Organometallic chemical vapor deposition (OMCVD) also appears to have the capability of growing high efficiency 60 GHz IMPATT structures. And OMCVD appears to be suitable for volume production. Both of the above approaches are being pursued by NASA and others.

60 GHz Receiver Technology

The receiver technology at 60 GHz is presently limited to cooled and uncooled image enhanced mixers. Typical well designed receivers employing uncooled mixer front ends easily achieve noise temperatures less than 1500 degrees Kelvin. Cooling the mixer to 70 degrees Kelvin can improve the noise temperature considerably. System noise figure improvement of 3 db is possible, which is equivalent to a 50 percent reduction of transmitter power. The receiver noise temperatures utilized in the link budget calculations were chosen as typical of those which can be achieved with image enhanced mixers. A 60 GHz receiver front end employing a cooled image enhanced mixer was assumed for the 525 degree Kelvin noise temperatures while an uncooled mixer was assumed capable of producing a receiver noise temperature of 1000 degrees Kelvin with a modest improvement over current technology.

MMIC Technology for Advanced Low Earth Orbit Applications

Future space stations are expected to require low cost microwave monolithic integrated circuit (MMIC) technology for adaptive transmit and receive antennas. Monolithic transmit and receive module technology, already under development at 20 and 30 GHz, can provide the technology base to meet these requirements at Ku through Ka bands. Considerable development effort will be required to extend this technology to 60 GHz, but promising approaches have already been identified.

Transmit modules will have digital phase shifters and digital power control, with power added efficiency optimized at each power level. All analog functions and digital interfaces will be on a single GaAs chip. The receive modules will have digital phase shifters, digital gain control, RF to IF conversion and the digital interface unit on a single chip. There may also ultimately be a 60 GHz transistor front end. The layouts of a 20 GHz transmit module and 30 GHz receive module are illustrated by Figures 10 and 11 respectively.

In considering the extension of this technology to 60 GHz, several things should be noted:

- o Once the technology is in hand, the cost required to implement a given function in MMIC will decline with frequency. This is so because chip area required tends to be a declining function of frequency.
- o The performance of MMIC passive components tends to decline quite slowly, or in some cases, improve with increasing frequency.
- o Passive switches, required for digital phase shifters, may be feasible, at 60 GHz, using existing GaAs MMIC techniques.
- o Several approaches that may yield monolithically compatible active devices with good performance at 60 GHz are already under investigation.

The above ideas are developed more fully in Reference 15.

REFERENCES

1. G.R. Welti, and Y.S. Lee, "Planning Assistance for the 30/20 GHz Program, Task 6 Final Report, Study of Intersatellite Links," NAS3-22905, Comsat Laboratories, Clarksburg, MD., Nov. 1981.

2. R.G. Wallace, and R. Kaul, "Spacecraft-to-Spacecraft Communications: Requirements, Designs, and Relative Cost/Benefits, Final Report," NAS5-25340, ORI Inc., Silver Springs, MD., 1979.

3. H. G. Kosmahl, "A Novel, Axisymmetric, Electrostatic Collector for Linear Beam Microwave Tubes," NASA TND-6093, Feb. 1971.

4. T. Inukai, "SS-TDMA Networking via ISL," in IEEE International Conference on Communications. New York: IEEE, 1981, vol. 4, pp. 70.6.1-70.6.5.

5. G.R. Welti, "Intersatellite Links for Multiple-Access Telephony," EASCON Convention. New York: IEEE, 1978, pp. 432-440.

6. D.K. Sachdev, and T. Chidambaram, "Intersatellite Links for International Communications," in IEEE International Conference on Communications. New York: IEEE, 1981, Vol. 4, pp. 70.2.1-70.2.6.

7. R.F. Filipowsky, and E.I. Muehldorf, Space Communications Systems. New Jersey: Prentice-Hall, 1965, p.198.

8. G.R. Welti, "Application of Intersatellite Links to Collocated Telecommunications Satellites," in International Telemetring Conference. North Carolina: Instrument Society of America, pp. 199-202.

9. H. Seunik, F. Gross, and F. Weinzierl, "High Power CW PPM-Focused TWT for Upper Q-Band," in International Electron Devices Meeting. New York: IEEE, 1977, pp. 128-131.

10. R.M. White, C.E. Enderby, and C.K. Birdsall, "Properties of Ring Plane Slow-Wave Circuits," IEEE Trans. Electron Devices, vol. ED-11, pp. 247-261, June 1964.

11. C.E. Enderby, "Ring-Plane Traveling-Wave Amplifier: 40 KW at 9 mm," IEEE Trans. Electron Devices, vol. ED-11, pp. 262-265, June 1964.

12. E.A. Ash, A. Pearson, A. W. Horsley and J. Froom, "Dispersion and Impedance of Dielectric-Supported Ring-and-Bar Slow-Wave Circuits," Proc. Inst. Electr. Eng., vol. 111, pp. 629-641, Apr. 1964.

13. H.G. Kosmahl, and R.W. Palmer, "Harmonic Analysis Approach to the 'Tunneladder,': A Modified Karp Circuit for Millimeter-Wave TWTAs," IEEE Trans. on Electron Devices, vol. ED-29, pp. 862-869, May 1982.

14. T.E. Seidel, R.E. Davis, and D.E. Iglesias, "Double-Drift-Region Ion-Implanted Millimeter-Wave IMPATT Diodes," Proc. IEEE, vol. 59, pp. 1222-1228, Aug. 1971.

15. D.J. Connolly, G. Anzic, and A.N. Downey, "The Role of GaAs ICs In Future Satellite Communications Applications," in Reliable, Survivable and Affordable Electronics, the 1983 Space Electronics Conf., 1983.

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TABLE 1. - LINK POWER BUDGET

Intersatellite Frequency = 61.500 GHz	
Bit rate = 274.00 MBPS	
M (Number of bits per symbol) = 2	
Transmitting Satellite Description	
Output power, dBW (0.076 watts)	-11.10
Antenna gain, dB (1.2 m. dia., 0.28 deg. HPBW)	55.22
Feed loss, dB	-3.00
EIRP, dBW	41.05
Antenna pointing error, dB (0.05 deg.)	-0.30
System Losses	
Margin, dB	-0.00
System aging effects, dB	-1.00
Random variation of elements, dB	-1.50
Propagation loss, dB (Range = 1843 km, sep. = 2.50 deg.)	-193.53
Receiving Satellite Description	
Antenna pointing error, dB (0.05 deg.)	-0.30
Feed loss, dB	-2.00
Antenna gain, dB (1.2 m. dia., 0.28 deg HPBW)	55.22
Received carrier power, dBW	-102.36
Received noise power density, dBW/HZ (T(R) = 525.)	-201.40
Bandwidth, dB (H_z) (274.00 MH_z, BT = 2.00)	84.38
Uplink noise contribution, dB (Uplink EB/NO = 20.00 dB)	1.11
Receiver noise power, dBW	-117.02
Link Carrier to Noise Power Ratio, dB	13.55
Hardware Implementation Loss, dB	-1.00
EB/NO, (dB) (BER = 1.0 E9)	12.55

TABLE 2. - CURRENT 60 GHz IMPATT DIODE DEVELOPMENTS

Laboratory	Sponsor	Power goal	P.A. Eff. goal	Material	Growth/profile approach
1. Hughes	(NASA-LERC)	1w	15%	GaAs	MBE/HYBRID DD
2. M/A - COM	(NASA-LERC)	1w	15%	GaAs	OMCVD/HYBRID DHS
3. Varian	(NRL)	1w	14%	InP	VPE/II
4. Hughes	(GSFC)	1.4w	14%	Si	MBE, VPE, II
5. Raytheon	(AFWAL)	2w	10 - 15%	GaAs	VPE
6. Raytheon	(AFWAL)	2w	15%	GaAs	MBE

VPE - Vapor phase epitaxy
DHS - Diamond heat sink
II - Ion implantation
DD - Double drift

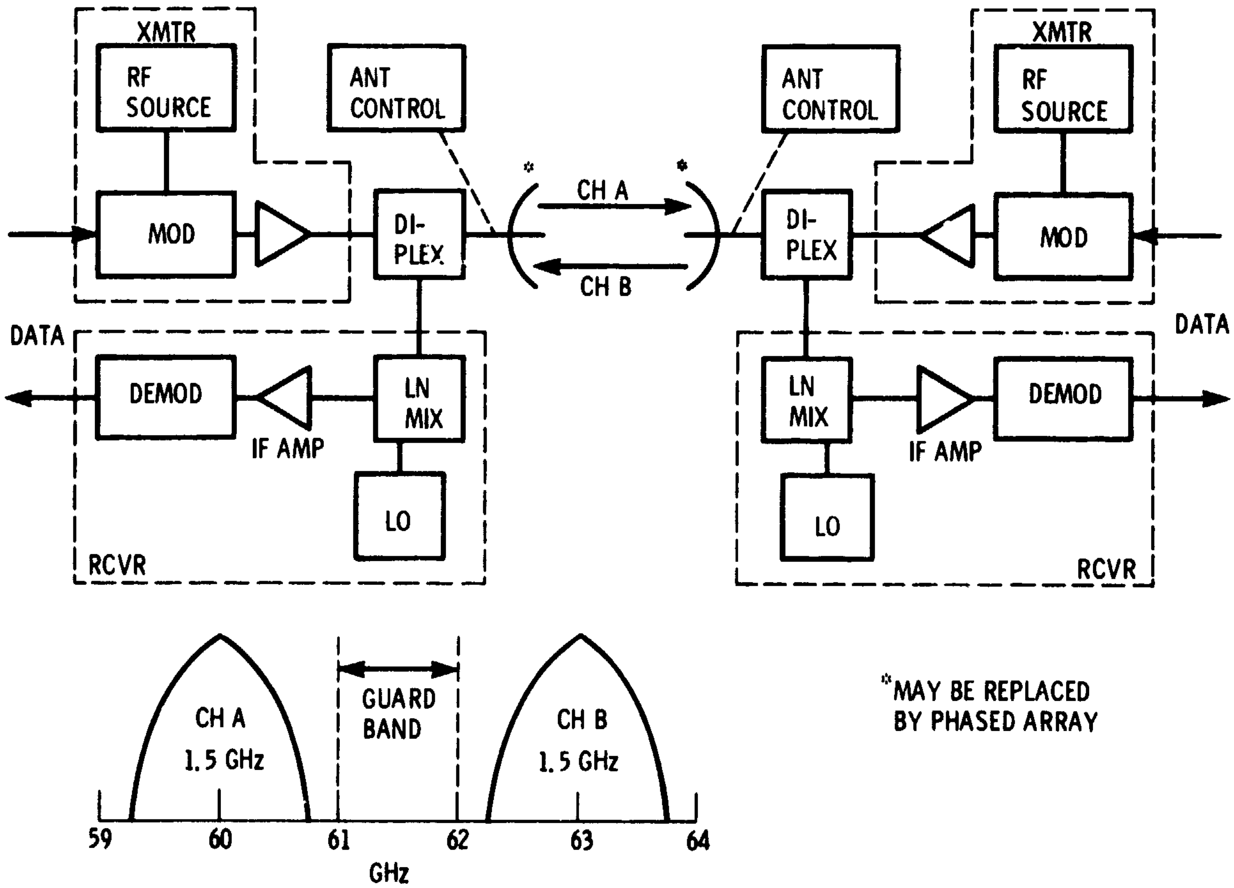

Figure 1. - 60 GHz intersatellite link configuration.

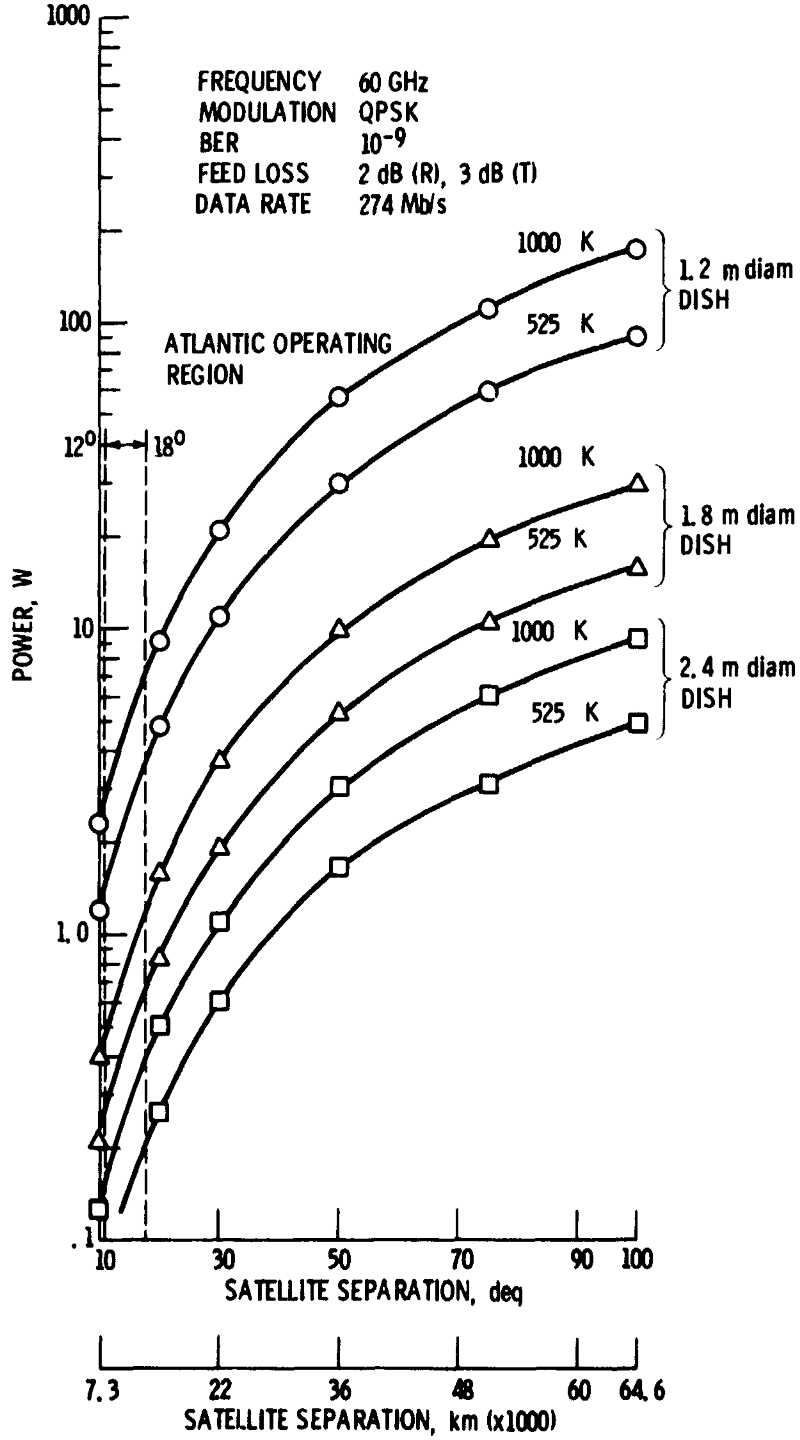

Figure 2. - GEO-GEO intersatellite link.

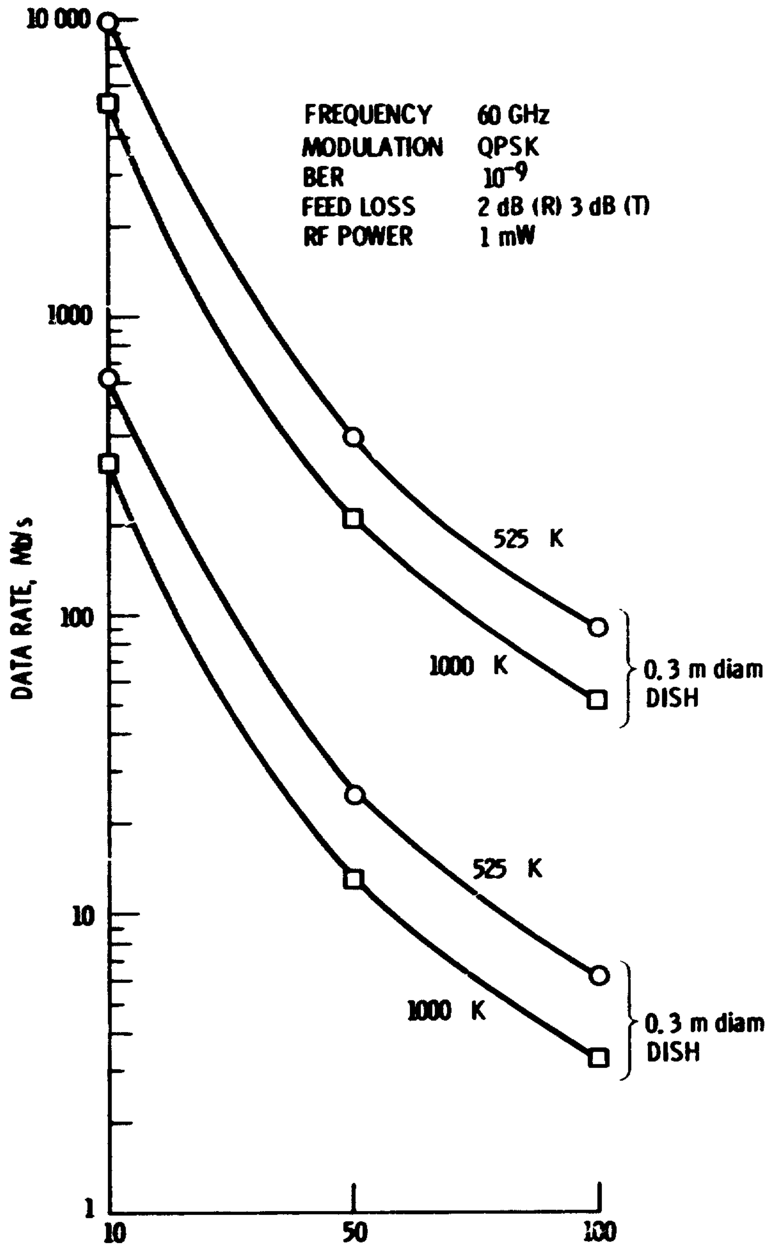

Figure 3. - LEO-LEO intersatellite link.

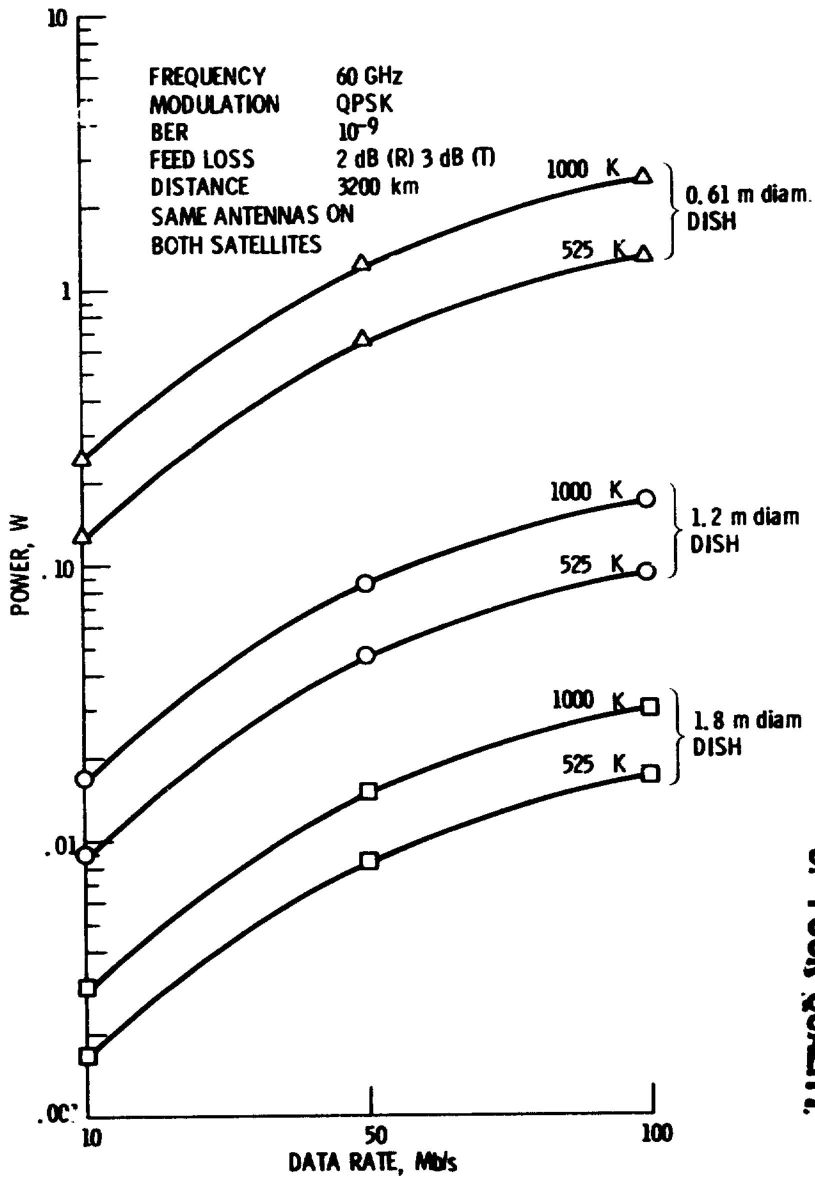

Figure 4. - LEO-LEO intersatellite link.

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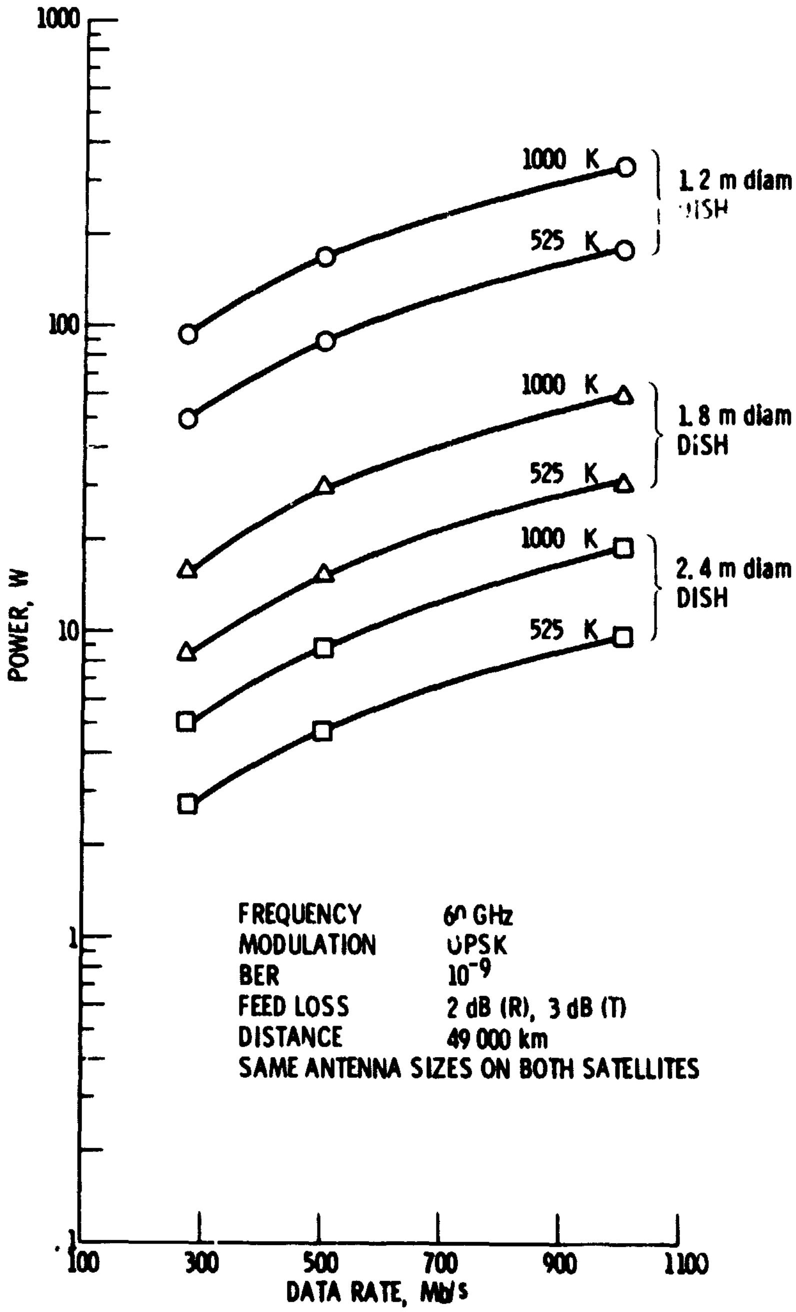


Figure 5. - LEO-LEO intersatellite link.

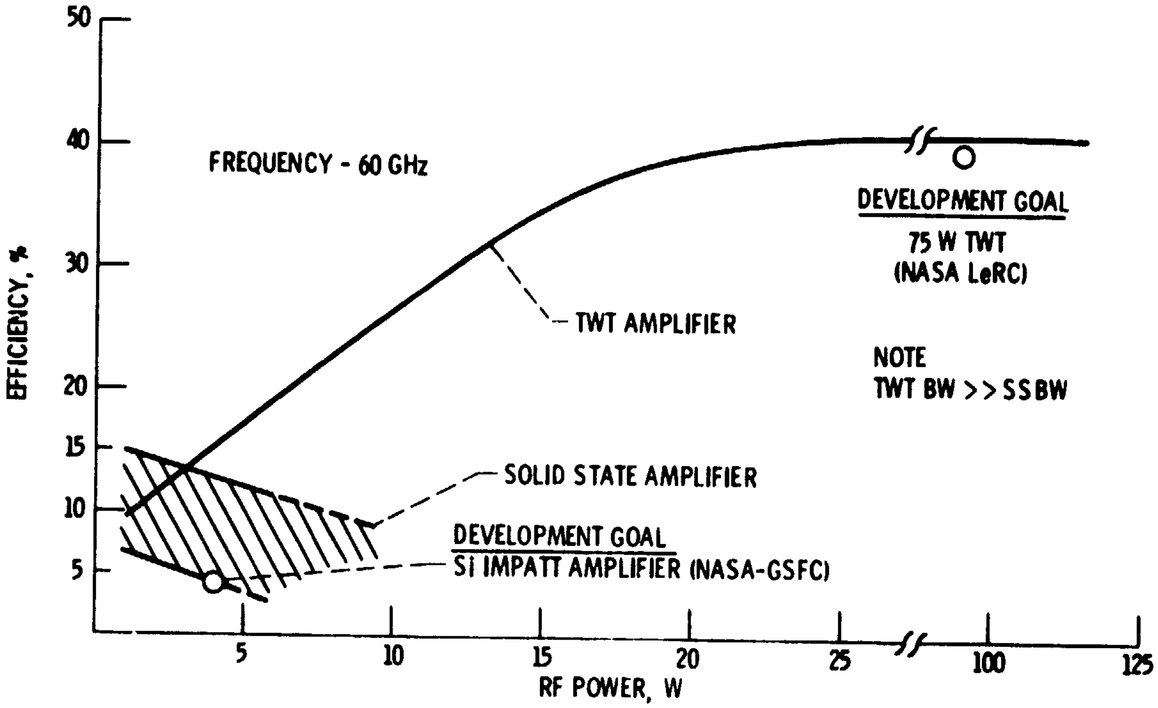
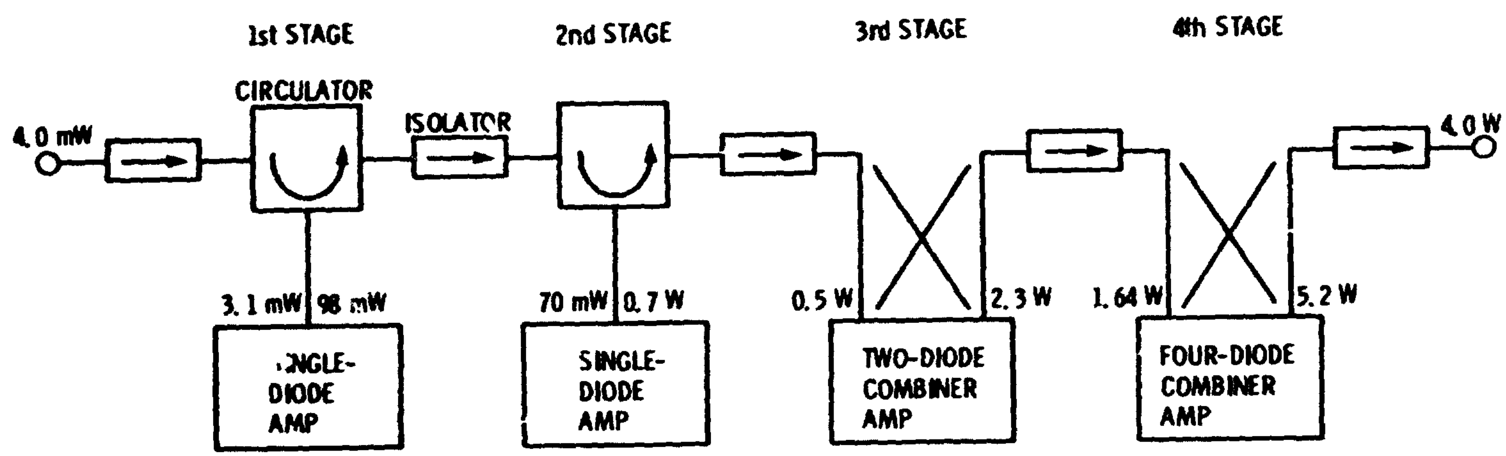


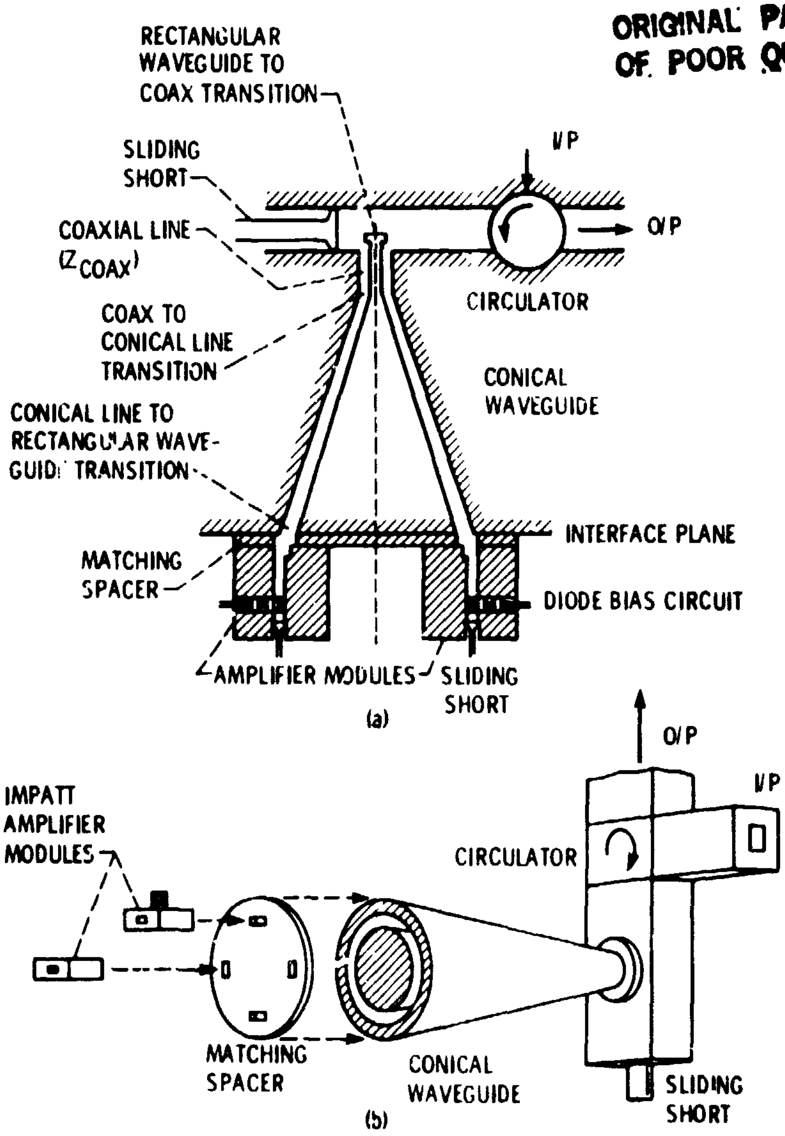
Figure 6. - RF power vs efficiency.



	1st STAGE	2nd STAGE	3rd STAGE	4th STAGE
GAIN (dB)	15	10	6.5	5.0
POWER ADDED (W)	0.095	0.63	1.84	3.56
COMBINING EFFICIENCY			92%	89%
DC INPUT POWER (W)	4	10	28.6	57.2

TOTAL DC INPUT POWER: 99.8 W
TRANSMITTER DC-TO-RF CONVERSION EFFICIENCY: 4.0%

Figure 7. - 60 GHz amplifier configuration.



CONICAL COMBINER: (a) SECTIONAL VIEW (b) EXPLODED VIEW

Figure 8. - 60 GHz conical line mm wave power combiner design for high power and wideband operation.

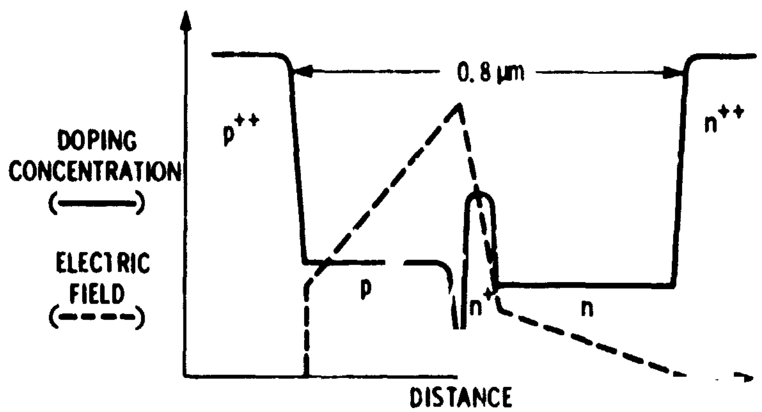


Figure 9. - Doping and electric-field profiles for a hybrid Read flat-hi-lo structure.

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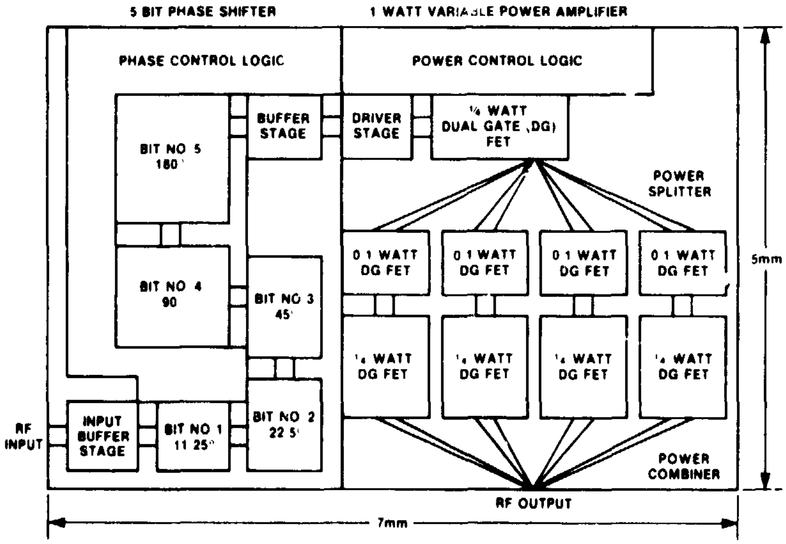

Figure 10. - 20 GHz GaAs monolithic transmit module.

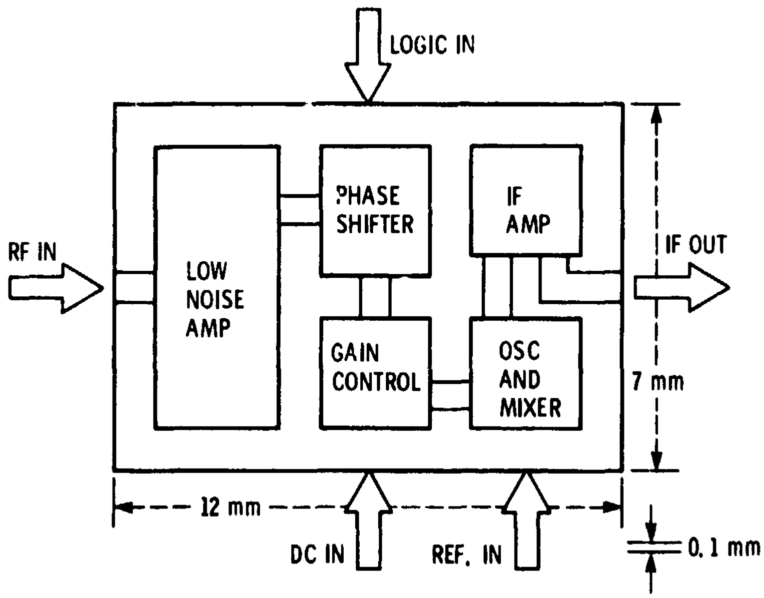

Figure 11. - 30 GHz monolithic receive module.