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MICROTECHNOLOGY IN TELECOMMUNICATIONS FOR SPACECRAFT COST AND MASS REDUCTION

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ABSTRACT

This paper examines the incorporation of both microelectronics and micromachining (termed microtechnologies) as applied to deep space telecommunication subsystems. Using the Pluto Fast Flyby Pre-Project as a main case study we have reduced the subsystem mass by 50%. This was accomplished via the use of advanced packaging {RF and digital multichip modules (MCMs) and Monolithic Microwave Integrated Circuits (MMICs) for the transponder and advanced GaAs power device technology for solid state power amplifiers }. Micromachined diplexers, filters, and switches using membrane-supported transmission line-technology (MIST-T) provide the potential to reduce subsystem form factor. Another way to reduce mission costs is in the use of both 32 GHz (at Goldstone Deep Space Network {DSN} facility) and 8.4 GHz (at Canberra and Madrid DSN facilities) downlink frequencies. This allows the data to bc returned faster, thereby saving both DSN and Mission Operation costs.

INTRODUCTION

What is microtechnology and how does it fit in with the Jet Propulsion Laboratory's (JPL's) "Faster, Better, and Cheaper" development philosophy for telecommunication systems for deep space applications? Microtechnology is interpreted to go beyond basic microelectronics and includes micromachining technology. By reducing subsystem mass we can utilize smaller (hence cheaper) launch vehicles. Increased technology insertion is a means to get science data back to earth faster and still reduce end-to-end project costs (including Deep Space Network and Mission Operations costs) and increase mission reliability. This paper is based upon the advancements of the Pluto Fast Flyby Pre-project Advanced Technology Insertion (ATI)* and JPL-supported advanced technology studies [1] which are leading to the realization of low cost planetary missions. Teamwork between JPL, the National Aeronautics and Space Administration (NASA), industry, government laboratories, the Department of Defense (DOD), and the university community is a key for our success. This is evident by the extensive author list for this paper.

Based on the Pluto Fast Flyby (PFF) pre-project effort, the telecommunication subsystem contributes the largest percentage of the spacecraft's dry mass at 15% (see Figure 1). In FY93 our goal was to reduce this mass (25kg) by a factor of two via the insertion of advanced microelectronics. Specifically, Monolithic Microwave Integrated Circuits (MMICs) micro-electronics such as GaAs Pseudomorphic High Electron Mobility Transistors (PHEMTs), Heterojunction Bipolar Transistors (HBTs), and traditional Metal Semiconductor Field Effect Transistors (MESFETs) have been used. Although not a part of the active electronics itself, our antenna technology is a crucial part of the subsystem design. By employing low mass advanced composites we are able to increase the antenna size and reduce the RF transmitter power requirement, which translates to less required prime power and amplifier development costs.

A current telecommunication subsystem block diagram of the FY94 subsystem is shown in Figure 2. One can quickly divide this subsystem into three distinct areas: antennas, transmitter, and transponder. Although the architecture appears quite standard, those whom are familiar with deep space communications will realize at least two traditional hardware boxes are no longer present (the Command Detector Unit - CDU and the Telemetry Modulation Unit - TMU). These functions have been merged into the transponder. In addition, we have two downlink frequencies to chose from (8.4 GHz and 32 GHz). After careful end-to-end mission cost studies we have concluded that using X-Band 70 m antenna stations at Canberra and Madrid and an array of three, 32 GHz, 34 m antenna stations at Goldstone is the quickest and cheapest method to get 1Gbit of data back to earth from Pluto to meet mission requirements. Ka-Band (32 GHz) has great promise for future communication satellites for both commercial and deep space applications.

TRANSPONDER

The transponder provides reception of command data (with a threshold of -158 dBm), and the transmission of coherent two-way ranging, delta differential one-way ranging (ADOR), and downlink telemetry. At the beginning of the PFF pre-project, we estimated that a transponder combined with CDU and TMU packaged separately would be approximately 6.3 kg using inherited

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technology. Under ATI funding we have initiated an effort to incorporate the CDU and TMU functions into the transponder, yielding a total component mass of 2 kg, Since PFF telecommunication subsystem is cross-strapped, our total transponder mass decreased from 12.6 kg down to 4 kg (or 68%). Figure 3 shows the technology trends for the transponder. One can immediately see that we have a major discontinuity in the mass curve. This is caused by the insertion of new technology. in this case we have benefited significantly from TRW IR&D and the government-sponsored ARPA MIMIC Program. Under the latter initiative, MMIC multifunction circuits have been realized via the establishment of standard design cell libraries and quality-controlled manufacturing processes.

Since we have limited ATI funding, we chose to competitively bid the X-Band digital receiver portion of the transponder. This unit is being developed by TRW. The mass goal is 1 kg with a threshold of -158 dBm. MMIC technology using GaAs PHEMT and HBTs for the RF front end and silicon ASIC/FPGAs for the digital baseband assembly are shown in Figure 4. In less than 10 months we hope to demonstrate a breadboard X-Band digital receiver. By using the same technology base, the exciter can be implemented, as well. The prime power consumption is slightly less than conventional approaches. However, in the future with cellular low power phone technology and 3V logic (even quantum integrated circuits[2]) the prime power can be significantly reduced.

Advanced packaging technology for both RF and digital assemblies is a major factor in the reduction of mass, as shown in Figure 3. Multichip Module (MCMs) packaging for digital circuits has been the prime focus of both government and commercial investment. However, the support for RF MCMS has just begun. As one goes up in frequency, material parameters and geometries effect signal loss, cross-talk, and packaging density. JPL, via its Director's Discretionary Funding, is beginning to address the area of high frequency packaging technology. Industry, DOD, universities, and NASA Research Centers are involved is this effort.

A major challenge for our ATI development is not only in the demonstration of the functionality of the components, but in the successful insertion of the technology into the mission itself. Reliability of MMIC devices, which do not have flight heritage, is a challenge which must be addressed early in the project. since future systems will have many multifunction MMIC components, it is important to employ qualified manufacturing lines (QML). The exact meaning and future requirements of a space-qualified line is on going. MMIC foundries are establishing high reliability processes to service commercial and government space customers. This approach allows the cost of MMIC qualification to be substantially reduced,

TRANSMITTER TECHNOLOGY

The next area that impacts mass and cost is in the realization of the proper EIRP (equivalent isotropic radiated power) to close the downlink. This involves a tradeoff between antenna aperture (mass) and RF transmitter power. Solid State Power Amplifiers (SSPAs) are a factor of 2-7 times less massive than traditional traveling wave tube amplifiers for X and Ka frequency bands {when requiring less than 20 W(RF) and 10 W(RF), respectively}. In addition to the mass aspect, we must demand that the SSPA efficiency be as high as possible. A Ka-Band 1.5 W SSPA unit has the potential of increasing our data rate by at least a factor of two; thereby, allowing greater science return and reducing mission operations costs.

Martin Marietta Corporation, under a competitive ATI award, developed a 32 GHz output module with a minimum 1.5 W RF power with 7 dB gain at 28% power added efficiency. The key to achieving and surpassing the project goals was with the use of advanced Pseudomorphic High Electron Mobility Transistor (PHEMT) technology. 13y surpassing our goals, we allow the system designers some new options which include: reduction of prime power for the subsystem (and perhaps the reduction of power subsystem mass as well) or the increase of data rate for the original prime power which is available. Figure 5 shows the development trend of 1 W Ka-Band SSPA technology based on IEEE Microwave Theory and Techniques Symposium Digest articles over the past six years with relationship to the accomplishments in this work[1]. We were able the demonstrate in less than five months a state-of-the art output module (Figure 6). The key was the IR&D and DOD support of advanced millimeter-wave power PHEMT device technology.

ANTENNA TECHNOLOGY

The High Gain Antenna for the Pluto Fast-Flyby Spacecraft was originally designated to be a flight spare 1.47 m Viking antenna. This unit incorporated an S-X band feed providing an X-band gain of 39 dBic. The ATI breadboard effort focused on reducing the Viking antenna mass of 5.9 Kg while maintaining or surpassing the RF performance. The Boeing Company, whose proposal was selected for the ATI program, provided a 1.5 m reflector fitted with a dual band feed (X-/Ka-Bands) with a mass of 2.8 kg. The reflector consists of twelve aluminum honeycomb ribs joining a circumferential honeycomb ring reinforcing the back side of the reflector shell. The shell is a 2.5-mm-thick graphite/cyanate ester. The resulting structure, which embodies a new hybridization between a semi-monocoque and all-honeycomb design, is very stiff and light enabling the more than 4070 decrease in mass. Figure 7 shows the final delivered antenna. This entire effort was completed in less than eight months. A key to this efficient development was that the tooling infrastructure was in place, due to past DOD-oriented projects.

MI CROTECHNOLOGY

Microtechnology is interpreted to go beyond basic microelectronics and includes micromachining technology. This is also referred to as Microelectromechanical Systems (MEMS) and it is emerging as the next frontier of enhanced, low-mass, high-performance components. One specific type of microtechnology is called Micromembrane Supported Transmission line - Technology (MIST-T). A subset of MIST-T is called microshield[3], which is being pioneered at The University of Michigan, MIST-T provides a quasi-planar approach to provide ultra low-loss transmission lines and densely packaged high frequency networks.

Using Figure 2 as a reference we can apply MIST-T to the diplexer, switches, transmitter and transponder (everything). However, we gain different advantages depending on the component. For the diplexer and switches we can reduce the component mass by - lkg, but the real gain is in the form factor reduction of the entire subsystem by 50%. For the transponder we can realize low-1oss preselect filters which reduce the noise figure of the system and in the transmitter the reduction of power splitter/combiner losses translates to higher data rates. An example of how MIST-T is being applied now is in PFF's ultra low-loss 32 GHz power splitters/combiners for transmitter SSPA[4] (Figure 8). This effort combined with our state-of-the-art results for the output power module described earlier provides greater output power and increased data rate for the same prime power allocation.

MIST-T's physical topology makes it very compatible with MMIC technology; thus, allowing for new architectures to be considered. The fabrication techniques to realize this technology is very mature and therefore not a cost driver.

MIST-T is being studied for launch and space survivability via JPL support with the University of Michigan.

CONCLUSION

The Pluto Fast Flyby (PFF) Pre-Project was used to show quantitatively the advantages which microtechnology in telecommunication for spacecraft cost and mass reduction. PFF has reduced its telecommunication subsystem mass from 25kg to 12.75kg with the incorporation of state-of-the art microelectronics technology. This mass savings translates into (using a figure of merit of $250K/kg) a saving of $3M to the project. By employing a dual frequency downlink (X- and Ka-Band) we can save an additional $8M in Deep Space Network and mission operations costs by getting the science data back to earth faster. The figures just quoted are first order; the benefit for future missions and commercial applications can be substantial and require further pursuit. Key technologies to achieve this advantage are MMICs and advanced digital and RF high density packaging. In addition, Micromembrane Supported Transmission line-Technology (MIST-T) provides the potential of another 10% savings in mass and a substantial reduction of the subsystem physical form factor in the spacecraft bus.

We have also identified the challenges of inserting new technology into flight systems. The survivability and qualification (a very arbitrary term) of new components and techniques need to be addressed; however, these are not a reason to inhibit new architectures and enable new lower-cost planetary missions.

ACKNOWLEDGMENTS

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We also appreciate the support of Rob Staehle, Stacy Weinstein, and Hoppy Price of the Pluto Fast Flyby Pre-Project Office. Special thanks to Chris Salvo, for early support of this work.

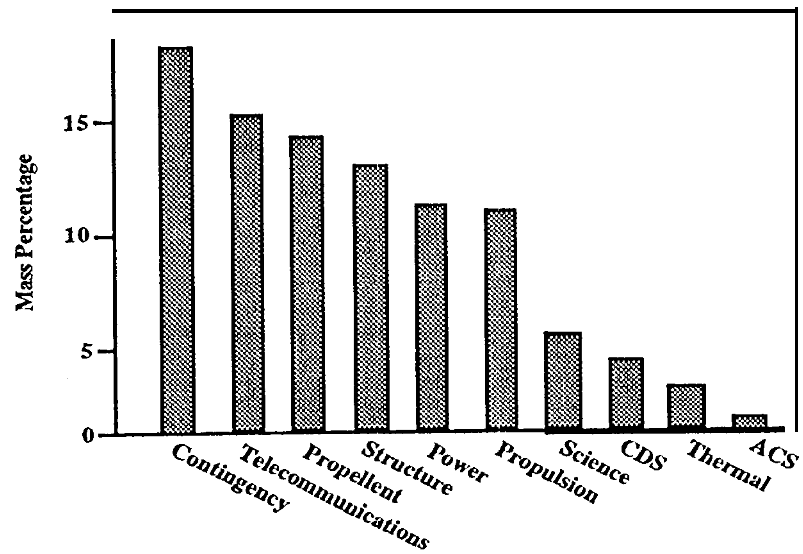

Figure 1. Spacecraft mass distribution for the FY93 baseline for the Pluto Fast Flyby pre-project. The telecommunication subsystem is a prime candidate for the insertion of new technology to reduce mass. For orbiters, the propulsion subsystem predominates.

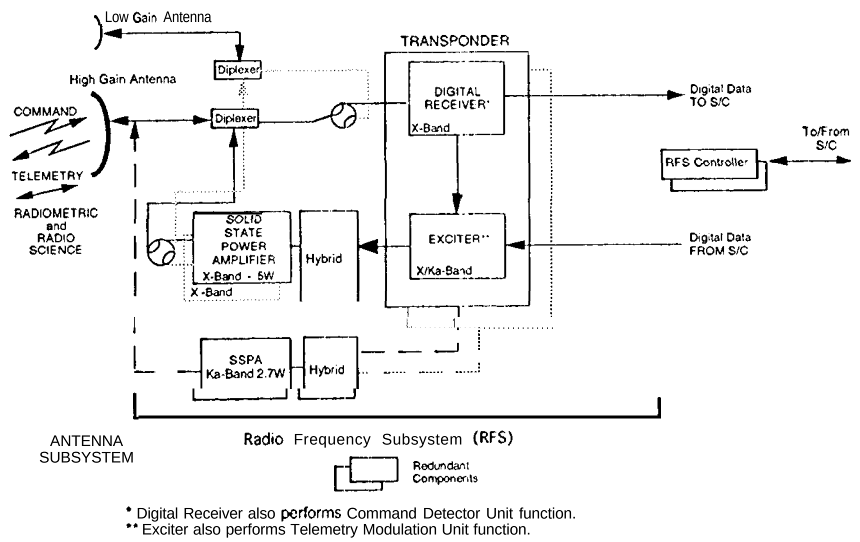

Figure 2. Block diagram of the FY94 Pluto Fast Flyby telecommunication subsystem. Novel changes to decrease subsystem mass and mission costs were: incorporation of CDU and TMU functions into the transponder, dual 8.4 and 32 GHz downlink frequencies, and loss mass antenna reflector technology. Our high-gain antenna is also redesigned for high efficiency, therefore, a much narrower beam (fostering the incorporation of a low-gain antenna for initial earth and emergency communications).

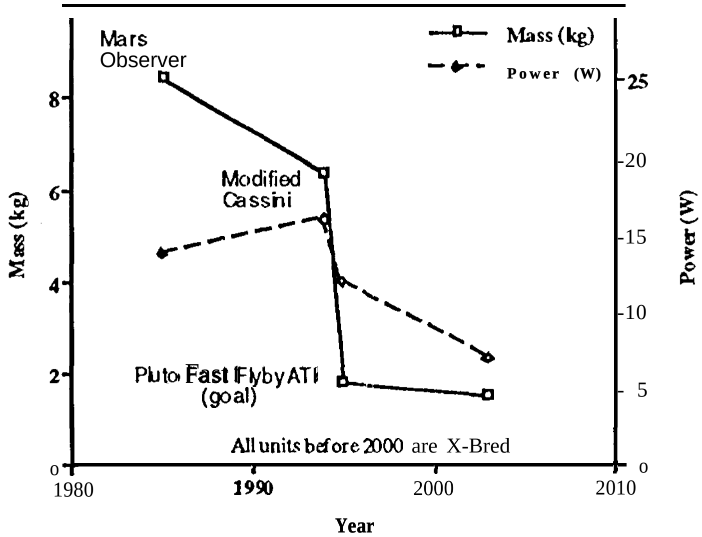

Figure 3. Technology trends for deep space transponders, command detector units, and telemetry modulation units. The discontinuity shown is due to the technology insertion of advanced packaging and Monolithic Microwave Integrated Circuit (MMIC) technologies. With the development of future low power logic and cellular phones the power consumption can be reduced in future designs.

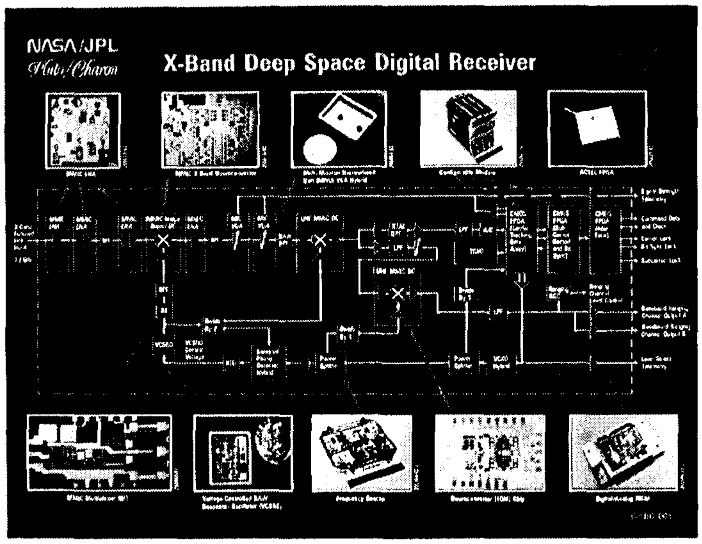

Figure 4. Pluto Fast Flyby Pre-Project Advanced Technology Insertion (ATI) X-Band Digital receiver which is being developed by TRW. The goal for this component is to have a mass <1 kg, require <4.5 W prime power, and have a threshold of -158 dBm. The key advanced technologies have been demonstrated (e.g., IR&D, ARPA's MIMIC program) and are prime for system insertion.

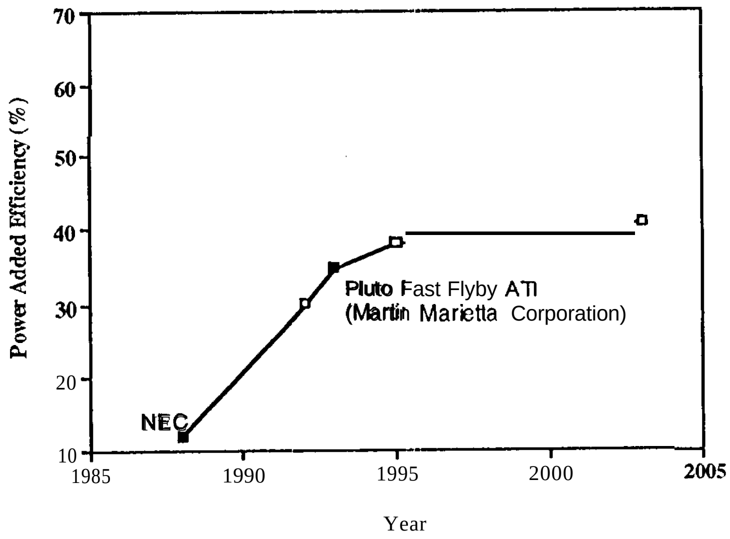

Figure 5. Technology trend for 32 GHz (Ka-Band) 1-W (RF) solid state power amplifiers.

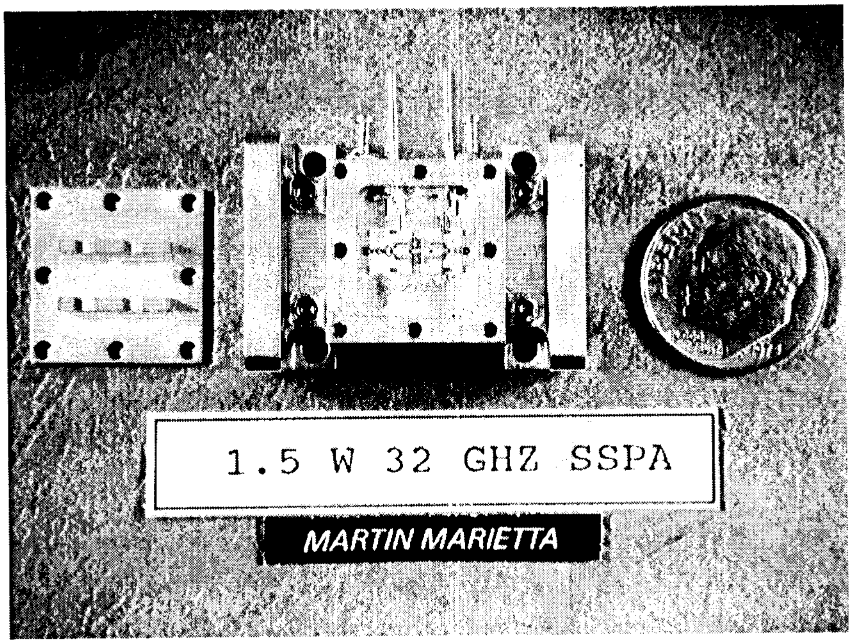

Figure 6. Martin Marietta Corporation, under a competitive Pluto Fast Flyby Pre-Project ATI award, developed a 32 GHz output module with a minimum 1.5 W RF power with 7 dB gain at 28% power added efficiency. The key to achieving and surpassing the project goals was with the use of advanced Pseudomorphic High Electron Mobility Transistor (PHEMT) technology.

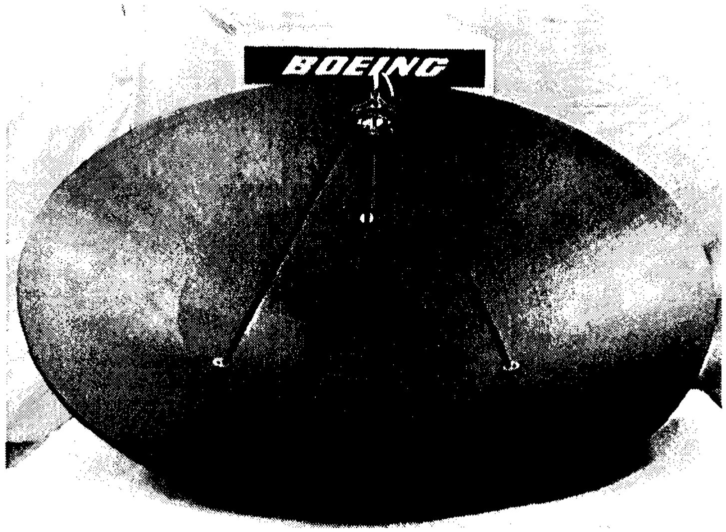

Figure 7. The Boeing Company, whose proposal was selected for the Pluto Fast Flyby Pre-Project ATI program, developed a 1.5 m reflector fitted with a dual band feed (X-/Ka-Bands) withamassof2.8 kg. Theoriginal baseline wasa Viking antenna whose mass was 5.8 kg.

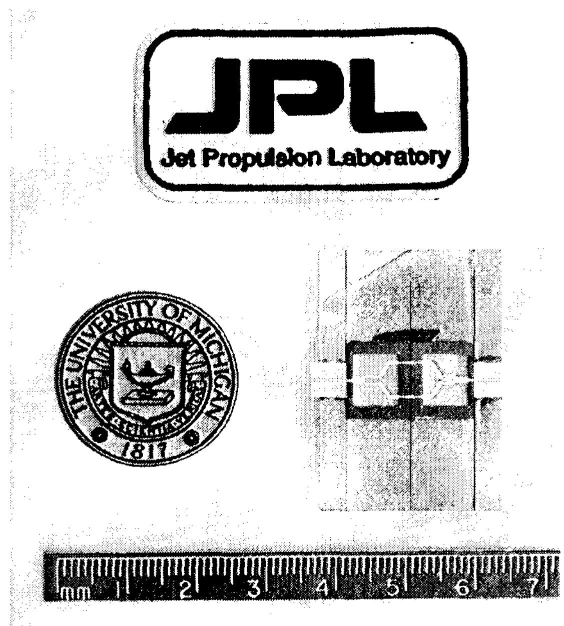

Figure 8. A 32 GHz power splitter/combiner using micromachined Micromembrane Supported Transmission Line-Technology (MIST-T) is being developed jointly by The University of Michigan and JPL. State-of-the-art results for low-loss will be reported at the upcoming IEEE Microwave Theory and Techniques Society International Symposium in San Diego[4]. This technology can significantly help reduce Telecommunication subsystem form factors by 50%.

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