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Compact High-Performance Reflector-Antenna Feeds and Feed Networks for Space Applications

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Abstract

Reflector antennas are widely used on satellites to communicate with ground stations. They simultaneously transmit and receive RF signals using separate downlink and uplink frequency bands. These antennas require compact and high-performance feed assemblies with small size, low mass, low passive intermodulation (PIM) products [1], low insertion loss, high power handling, and low cross-polar levels. The feeds must also be insensitive to large thermal variations, and must survive the launch environment. In order to achieve these desirable features without prototyping and/or bench tuning, Custom Microwave Inc. (CMI) has combined integrated RF design, precision CAD, and a precision manufacturing technique known as electroforming to closely integrate the various components of a feed or feed network, thereby achieving small size while maintaining high RF performance [2]. In addition to close integration, electroforming eliminates split joints and minimizes flanges by allowing several components to be realized in a single piece, making it the ideal manufacturing technique for ultra-low passive-intermodulation applications. This paper describes the use of precision design CAD tools along with electroforming to realize high-performance feed assemblies for various communication frequency bands for fixed satellite, broadcast satellite, and broadband satellite services.

Keywords: Reflector antenna feeds; feed networks; satellite communication; satellite broadcasting; intermodulation distortion; design automation; electroforming

1. Integrated Design Approach

Over the past ten years, CMI has designed a large number of complex antenna feed systems for communications and/or tracking that operate over single or multiple frequency bands, with dual-circular or dual-linear polarization. Most of these designs were realized without the need for prototyping or bench tuning. The efficiency of the design process has four key factors:

- The accuracy of the initial design (starting geometry).
- The numerical speed of the analysis and optimization routines.

- The final analysis and optimization, accounting for manufacturing tolerances and thermal excursions.
- The use of flight-proven parts, materials, processes, and design practices.

Feed-design heritage and expertise, along with appropriate design tools, are used to synthesize starting geometries of the various components for the feed assembly. These may include the horn, turnstile junction, matching section, filters, diplexers, combiners/dividers, polarizers, ortho-mode transducers, etc. It is important that the RF design team work very closely with the mechanical and manufacturing engineers to ensure that the feed is designed for manufacturing and assembly. The integrated feed assembly needs to be analyzed and optimized, including all of the piece parts, before finalizing the overall design.

Analysis and optimization of the entire feed is performed using *μWave Wizard* from Mician GmbH, a leading commercial software package in the field of antenna-feed design. This package features versatility, accuracy, computational efficiency, and a user-friendly interface. Analysis speed is addressed by proper choice of the full-wave method for the respective structure. A variety of full-wave analysis techniques are available to address structures from the simplest to the most complex with the highest efficiency. *μWave Wizard* is capable of fast optimization of entire antenna feeds with flexible definition of the components' geometries and various optimization strategies. The optimization routines are extremely flexible, and converge rapidly without compromising the accuracy of the solution. In addition to optimizing performance based on scattering parameters, *μWave Wizard* also allows the simultaneous optimization of co-polar and cross-polar patterns [3], which is a very powerful feature in optimizing overall RF performance for antenna feeds, as shown in Figure 1.

Thermal effects on RF performance are included in the RF design process. The operating-frequency bandwidths are expanded, based on the coefficient of thermal expansion (CTE) of the waveguide material, to include the effects of temperature extremes on the physical size of the part. Temperature effects are also included in the analysis to determine the impact on insertion loss. Figure 2 shows a typical response of the return loss for a Ku-band feed over hot, cold, and ambient temperatures, measured at CMI's environmental test facility. Except for the shift in frequency response due to expansion and contraction of the hardware, there were no significant changes over temperature. This is typical of tuning-less hardware with precision manufacturing.

Peak-power handling is also accounted for in the early stages of the RF design process. Internal features are carefully selected to ensure that high-power handling capability is met, while maintaining high RF performance and manufacturability. Appropriate constraints are imposed to maintain minimum gaps and eliminate sharp corners during the design optimization. The final design is analyzed, using *Microwave Studio* [4] from Computer Simulation Technology, to calculate peak voltages. Multipaction voltages and peak power handling are then determined using ESA standards [5].

Ultra-low-passive-intermodulation (PIM) performance is made possible by eliminating tuning screws and split joints, while

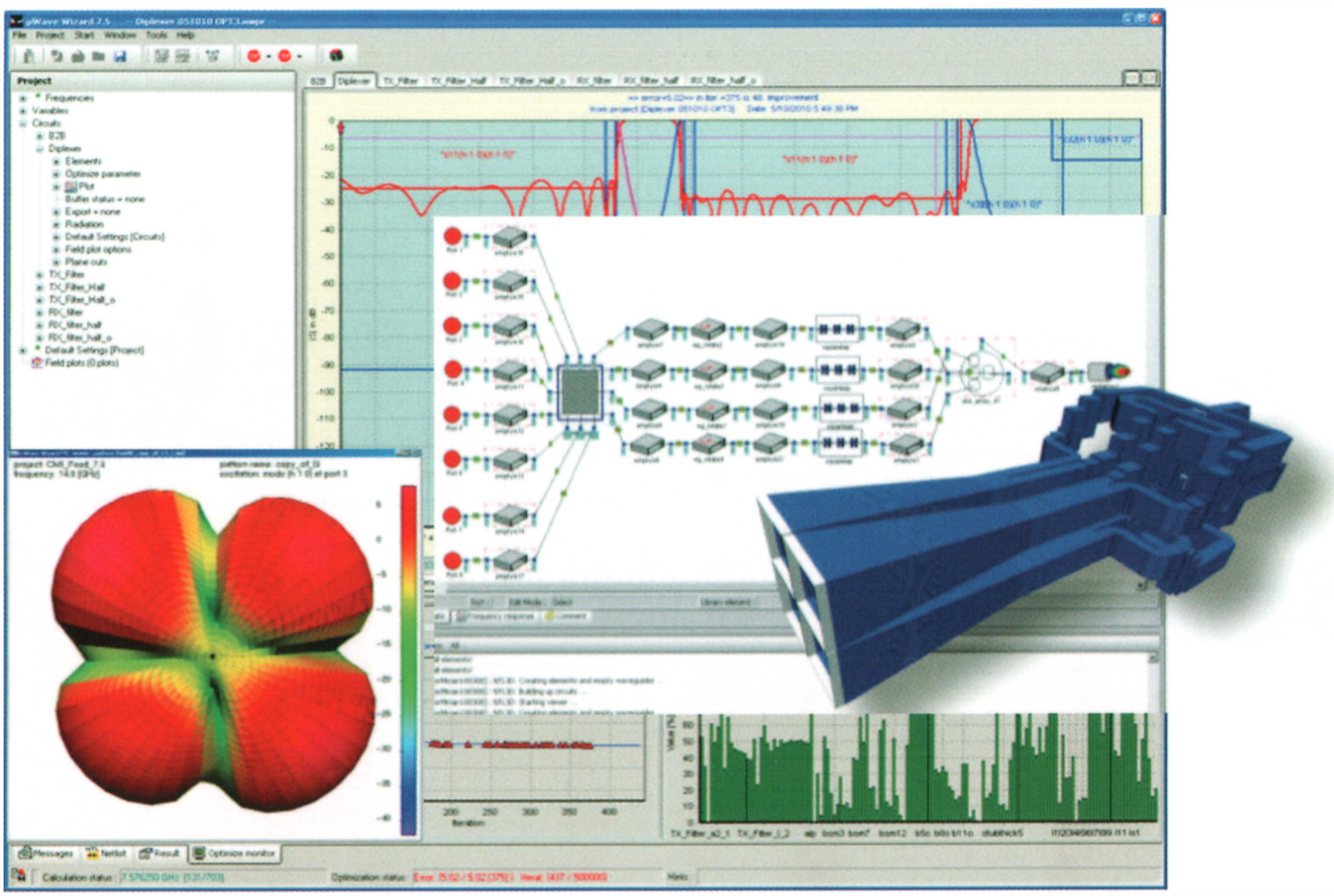

Figure 1. The analysis and optimization of a tracking feed using *μWave Wizard*.

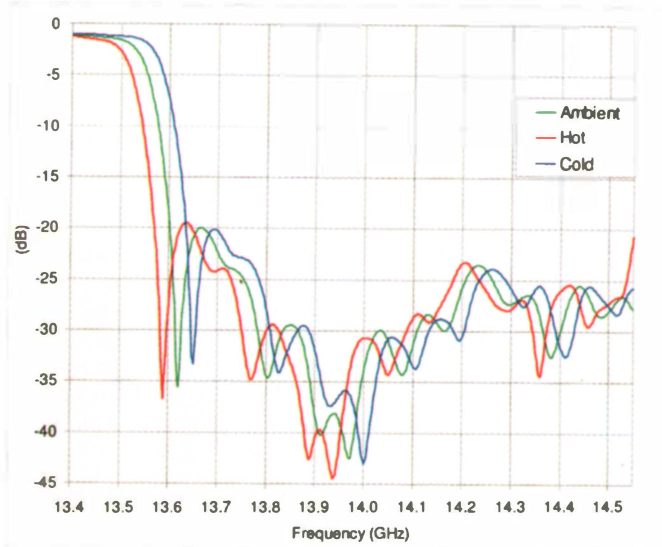

Figure 2. The measured return loss over a range of temperatures for a Ku-band feed.

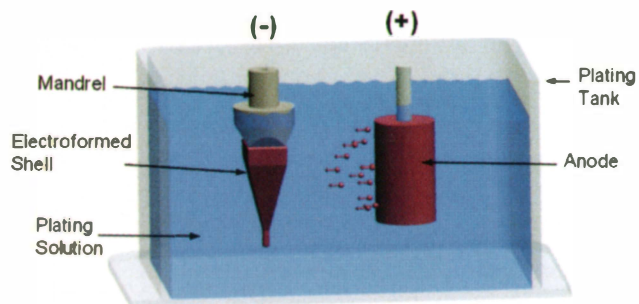

Figure 3. The electroforming process.

minimizing flange connections. This is achieved by precision fabrication using electroforming, which is discussed in more detail in the next section. When flanges are required, they are designed for low-passive-intermodulation performance. CMI has developed space-qualified low-passive-intermodulation flanges that work over extreme temperature ranges for various satellite communication bands.

In addition to RF design, detailed structural design and analysis of the feed assembly needs to be performed, in order to arrive at an optimal geometry for the feed assembly. Appropriate wall thicknesses, mounting brackets, stiffeners, and flanges need to be applied to the internal three-dimensional structure created by RF design. Finite-element analysis, based on NEi *NASTRAN* [6], is used to ensure that the feed assembly has adequate safety margins under thermal, static, and dynamic environments. It is also important to maintain strict adherence to using flight-proven parts, materials, processes, and design practices for these feeds, to avoid delays in the design process and to reduce overall program risks. Before fabrication, detailed steps, including in-process drawings and inspection points, are generated to define the manufacturing flow of the feed assembly.

2. Precision Manufacturing

In order to realize high-performance feeds, conventional manufacturing techniques, such as mill, lathe, or electro-discharge

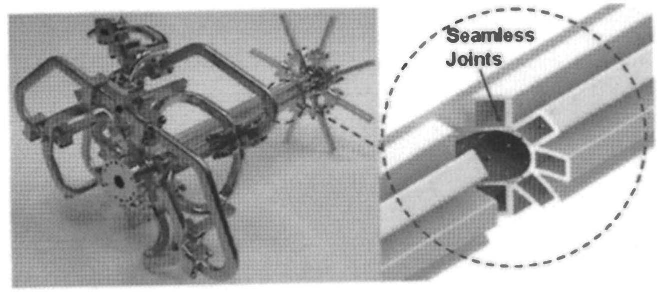

Figure 4. Seamless joints for the TE_{21} mode coupler in an eight-way tracking coupler.

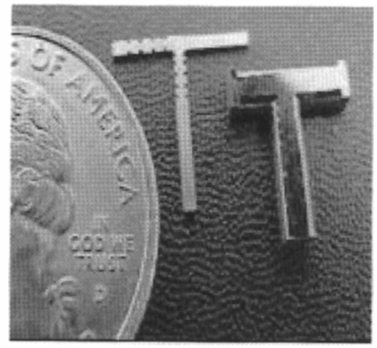

Figure 5a. The mandrel and electroform for a 166/183 GHz diplexer.

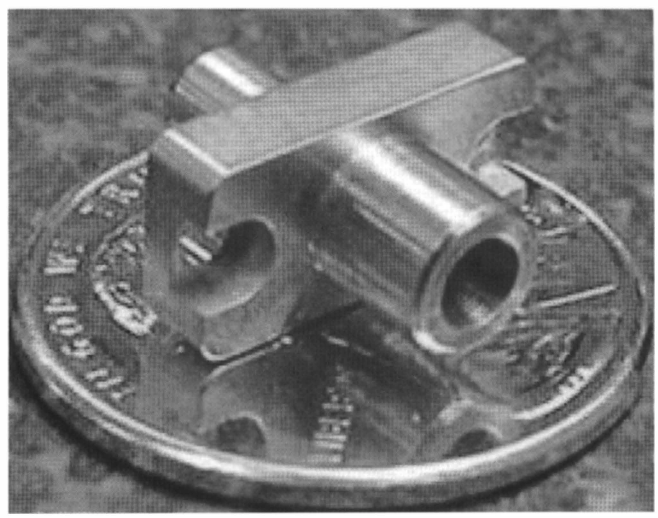

Figure 5b. An electroformed 650 GHz corrugated horn.

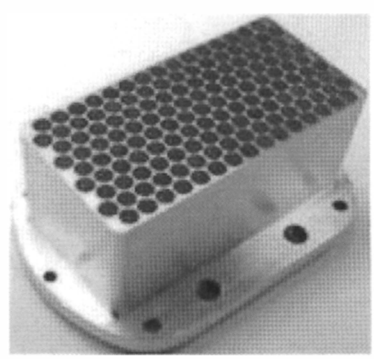

Figure 5c. A 1.2 THz array (40 mm × 20 mm) with 139 horn elements.

machining, require split joints and numerous flange connections to allow access for machining internal features. This generally leads to increased spacing and larger components. We use a precision manufacturing technique known as electroforming [7] to eliminate constraints associated with these other techniques. CMI has been using this technique to produce hardware for space applications for the past 30 years.

Electroforming is a process where a metal component is fabricated by electro-deposition onto a mandrel in a plating bath, as shown in Figure 3. Subsequent removal of the mandrel results in a shell with the desired internal features. Examples of parts that can be realized using electroforming are shown in Figures 4 and 5. Electroforming provides the following benefits:

- Very high precision: We have manufactured waveguide components up to 1.2 THz using electroforming. The high mechanical precision permitted by electroforming allows high-performance antenna feeds to be produced without the need for tuning screws. This in turn improves power handling, and further reduces passive-intermodulation risks. Tolerances are limited by the accuracy of the machined mandrel, which can be as tight as ±0.0002 in.

- Inspection of internal features: Internal features can easily be inspected on the mandrel. The electroformed shell becomes an exact mirror image of the mandrel.

- Uniform internal plating: If internal plating is required, it is first applied on the mandrel, before electroforming. This results in much more uniform plating than is achieved by plating inside a component after fabrication, as would be the case with other manufacturing methods.

- Fabrication of complex shapes in a single piece: Electroforming is ideally suited for manufacturing high-precision parts with very complex internal geometries in a single piece, without joints. This provides the designer with greater freedom to choose and locate internal features, allowing the potential for higher RF performance, while maintaining a compact envelope.

- Ultra-low-passive-intermodulation hardware: The absence of tuning screws and split joints, and a significant reduction in flange connections, make this process ideally suited for passive-intermodulation-critical hardware.

3. Feed Assembly Examples

The following subsections provide examples of high-performance antenna feeds produced using the methods discussed above in this paper.

3.1 Full C-Band Feed

An ultra-compact full C-band feed with dual-band (transmitting and receiving) and dual-circular polarization (LHCP and RHCP) was designed and built using this integrated approach. This was done within a relatively short time, including space qualification and testing for high-power handling, passive intermodulation levels, and thermal (bulk as well as gradient) RF performance. The horn was included in the design of the feed network to ensure that the overall feed performance of the feed assembly was met. The tuning-less high-performance electroformed network met all specifications without any hardware iterations. In addition to the tight schedule, the challenge was to design a unit with a very low axial ratio that fit within one-sixth the volume of the incumbent design, which was based on discrete-component technology.

Electroforming was used to achieve tight tolerances of up to ±0.0005 in, required for this tuning-less high-performance device. The use of electroforming also allowed this complex network to be built with a minimum number of flanged connections.

A summary of the measured performance is given in Table 1. Excellent agreement was achieved between measurements and simulations for all electrical parameters. An example of the measured and simulated on-axis axial ratios is shown in Figure 6. Typical co-polar and cross-polar patterns, measured in our anechoic chamber, are shown in Figure 7, along with simulated patterns.

CMI's resulting full C-band four-port circularly polarized feed is shown in Figure 8. The same concept and much of the same hardware could be used for a dual-band, dual-linear-polarization (LP) full C-band feed. We have space qualified a four-port linearly polarized C-band feed, which is also shown in Figure 8. Most of

Table 1. A summary of the measured performance of a four-port circularly polarized C-band feed.

Parameters	Measured Performance
Frequency, GHz	Tx: 3.625 – 4.2, Rx: 5.85 – 6.425
Axial Ratio	< 0.2 dB on axis
Insertion Loss	Tx: < 0.15 dB, Rx: < 0.05 dB
Return Loss	Tx: > 28 dB, Rx: > 32 dB
Isolation	RHCP ↔ LHCP > 25 dB Rx ↔ Tx > 60 dB
Peak Power	10 kW multipaction
PIM	< -140 dBm, 7th order
Edge Taper	20 dB (±30°) typical
Cross-Polar Levels	< –38 dB (±30°) relative to peak
Size, Feed	28.5"(L) × 12"(W) × 12.7"(H)
Mass, Feed	< 12 Kg (with brackets)

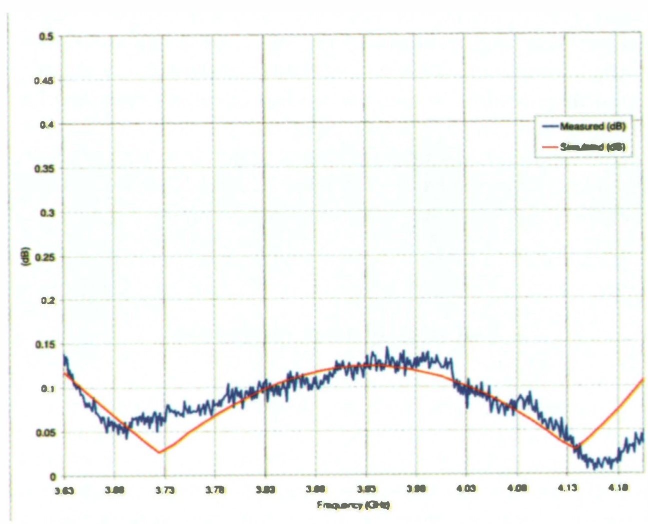

Figure 6. The measured on-axis axial ratio compared to the simulated response.

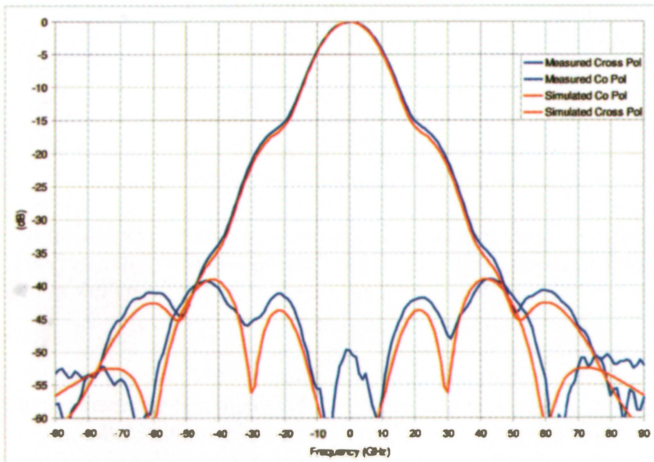

Figure 7. The measured and simulated co- and cross-polar patterns in the 45° plane.

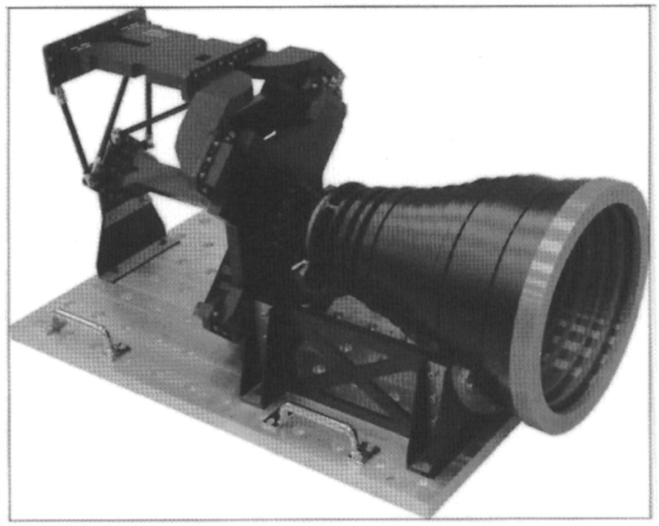

Figure 8a. An ultra-compact dual-band dual-circularly polarized C-band feed.

the components were identical to those used for the circularly polarized feed.

3.2 Ku-Band Feeds

We also developed a line of compact space-qualified Ku-band feeds. These feeds provided very high RF performance in a compact layout. The absence of tuning screws provided high power handling and very low passive intermodulation at extremely low temperatures. These feeds have been tested, and showed no evidence of third-order passive intermodulation with carries of up to 150 W at $-120°$C with a noise floor below -145dBm. A typical plot for a thermal passive intermodulation test is shown in Figure 9. These feeds can easily be configured as linearly polarized two-port Tx/Rx or dual circularly polarized four-port Tx/Rx feeds. The modular approach provides flexibility in configuration and functionality. Table 2 provides a summary of the measured performance for a four-port linearly polarized feed. Figure 10 shows a two-port linearly polarized feed and a four-port linearly polarized feed. Circularly polarized functionality was easily achieved by including a 90° polarizer between the horn and the ortho-mode transducer. This feed is shown in Figure 11. CMI has also developed other feeds with combined circularly polarized and linearly polarized functionality. A feed that is dual circularly polarized for transmitting and single linearly polarized for receiving is also shown in Figure 11. Typical measured return loss and isolation performance values are shown in Figure 12 for a four-port linearly polarized feed.

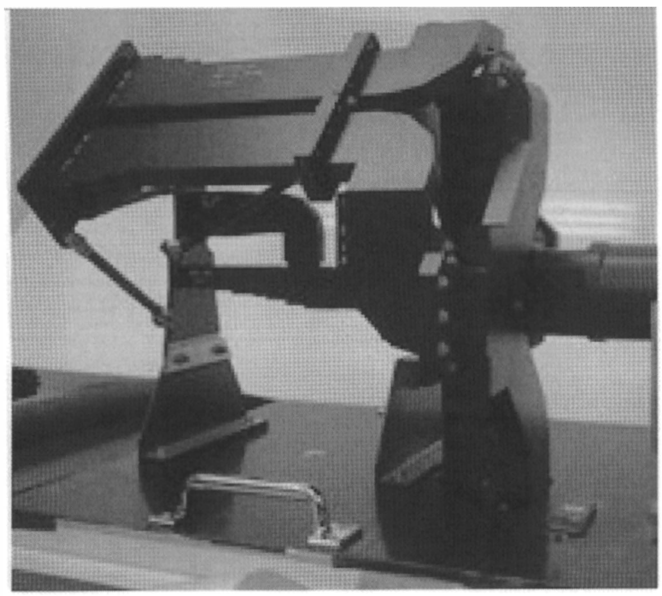

Figure 8b. A dual-band dual-linearly polarized C-band feed (horn not shown).

3.3 K-Ka-Band Network

A compact K- and Ka-band, dual-circularly polarized feed network was designed, built, and tested in the short period of three months. Thirty space-qualified units followed within six months. This could not have been possible without the integrated approach. The measured performance for all 30 units was very consistent. This is a common trait associated with precision machining, electroforming, and process control. The feed network is shown in

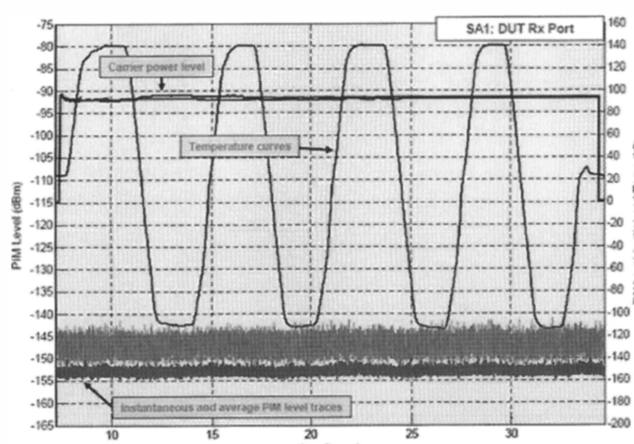

Figure 9. A typical plot for a thermal passive intermodulation test of a Ku-band feed.

Table 2. A summary of the measured performance of a four-port linearly polarized Ku-band feed.

Parameters	Measured Performance (4-P LP)
Frequency, GHz	Tx: 10.95 – 12.75, Rx: 13.75 – 14.50
Insertion Loss, dB	Tx: < 0.20, Rx: <0.25
Return Loss, dB	Tx: > 22, Rx: > 21
Isolation, dB	VP ↔ HP > 60 Tx ↔ Rx: > 70 at Tx; > 50 at Rx
Peak Power	> 9.6 kW multipaction
PIM, 3rd Order	< –140 dBm
Edge Taper	20 dB (±30°) Typical
Cross Polar	> 40 dB (±30°)
Size	< 15" Long
Mass	< 2.25 Kg

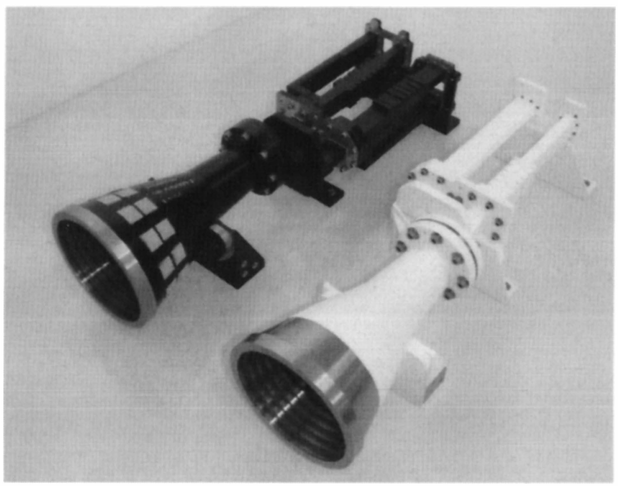

Figure 10. Compact Ku-band two-port linearly polarized and four-port linearly polarized feeds.

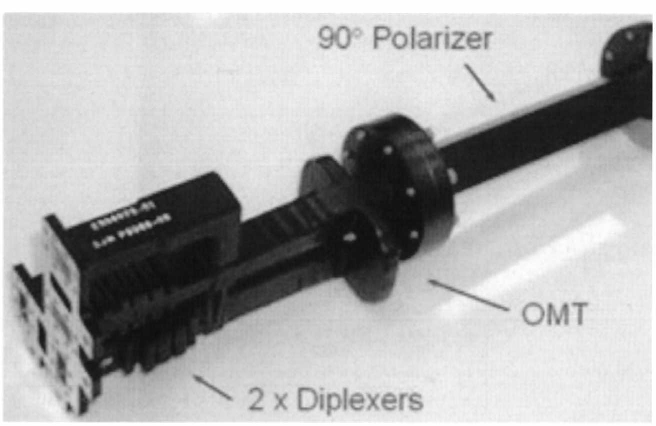

Figure 11a. A compact Ku-band four-port circularly polarized feed (horn not shown).

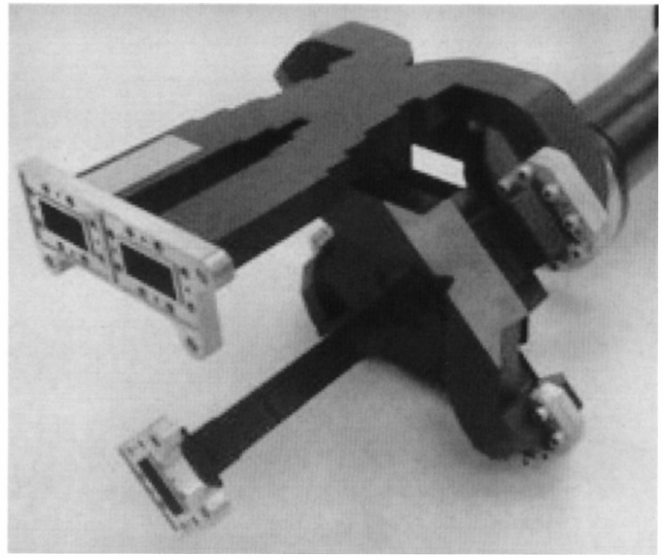

Figure 11b. A compact Ku-band feed with circularly polarization for transmission and linear polarization for reception (horn not shown).

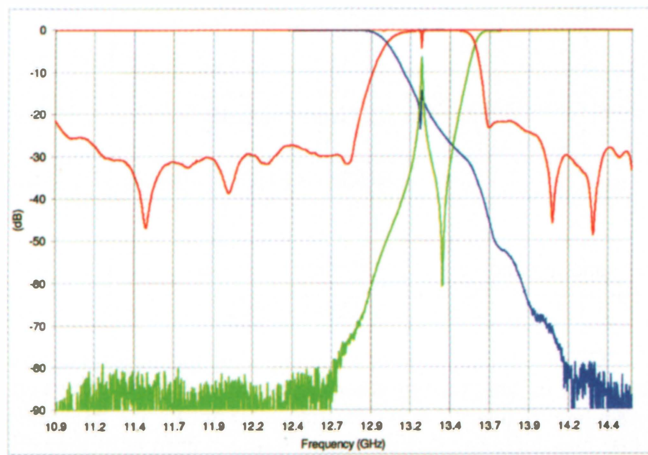

Figure 12. The measured return loss and rejection for a CMI four-port linearly polarized feed.

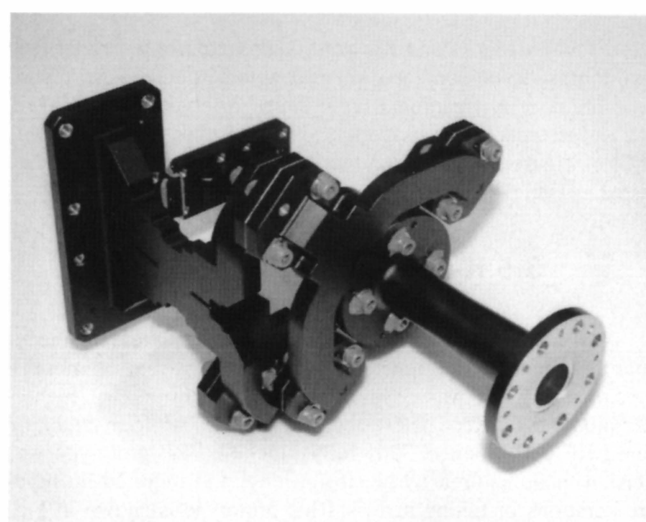

Figure 13. An ultra-compact dual-band (K-Ka) feed network.

Table 3. A summary of the measured performance of a compact four-port circularly polarized K-Ka feed.

Parameters	Measured Performance
Bandwidth	K-Band: 5% Ka-Band: 3%
Axial Ratio	K-Band: < 0.2 dB Ka-Band: < 0.1 dB
Insertion Loss	< 0.1 dB
Return Loss	> 30 dB
Isolation	RHCP ↔ LHCP > 30 dB Ka ↔ K > 60 dB
Peak Power	> 3.8 kW Multipaction
PIM	< -140 dBm
Size	4"(L) × 3"(W) × 4"(H)
Mass	< 350 g

Table 4. A summary of the measured performance of a low-profile four-port circularly polarized K-Ka feed.

Parameters	Measured Performance
Bandwidth	K-Band: 10% Ka-Band: 6%
Axial Ratio	K-Band: < 0.34 dB Ka-Band: < 0.13 dB
Insertion Loss	K-Band: < 0.4 dB Ka-Band: < 0.2 dB
Return Loss	> 28 dB
Isolation	RHCP ↔ LHCP > 30 dB Ka ↔ K > 70 dB
Peak Power	> 3.8 kW Multipaction
Size	< 2.1" ∅ × 4.7" Long
Mass	< 300 g (flight)

Figure 13, and Table 3 shows a summary of the measured performance. This unit was so compact that a waveguide extension was required to adapt it to the existing footprint for the mounting brackets and the horn. This extension is shown in front of the network in Figure 13.

3.4 Low Profile K-Ka Band Network for Feed Array

A low-profile K- and Ka-band dual-circularly polarized feed network was developed for tight packaging in a feed-array configuration. A fully functional tuning-less prototype was designed, built, and tested within six months. The prototype feed network is shown in Figure 14, and a summary of the measured performance is listed in Table 4.

3.5 K-Ka-Q Band Network

A tri-band dual-circularly polarized feed network for the K, Ka, and Q bands was designed, built, and tested within six months. Precision RF CAD was used extensively to ensure that higher-order modes were kept below acceptable levels while maintaining desired RF performance. This fully functional RF prototype was precision manufactured by electroforming, and required no hardware iterations or tuning screws. This prototype is shown in Figure 15. A summary of the measured performance is given in Table 5.

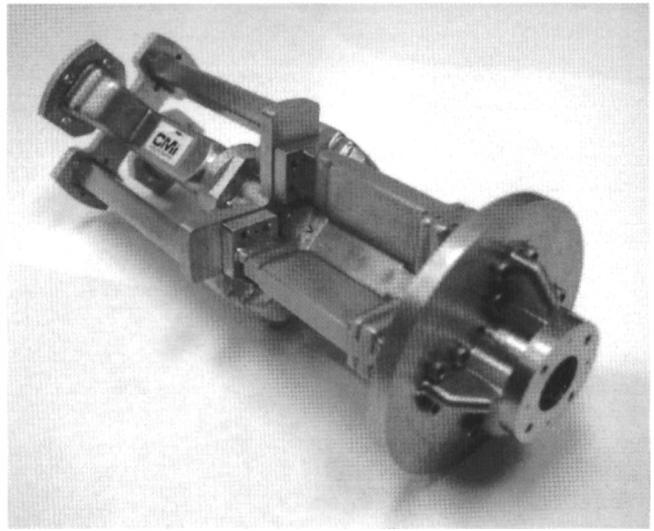

Figure 14. An ultra-compact dual-band (K-Ka) feed network.

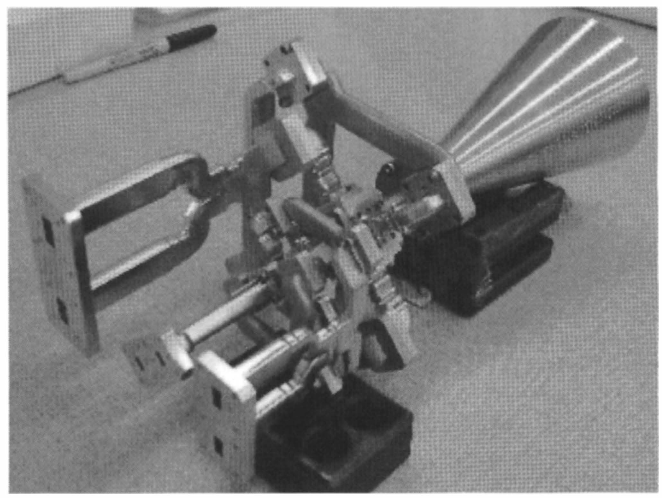

Figure 15. An ultra-compact tri-band K-Ka-Q six-port circularly polarized feed.

Table 5. A summary of the measured performance for a six-port K-Ka-Q-band feed.

Parameters	Measured Performance
Bandwidth	K-Band: 5% Ka-Band: 3% Q-Band: 5%
Axial Ratio	K-Band: < 0.20 dB Ka-Band: < 0.50 dB Q-Band: < 0.60 dB
Insertion Loss	K-Band: < 0.5 dB Ka-Band: < 0.4 dB Q-Band: < 0.3 dB
Return Loss	> 26 dB
Isolation	RHCP ↔ LHCP > 20 dB K ↔ Ka > 80 dB at K; > 70 dB at Ka; > 70 at Q K ↔ Q > 80 dB at K; > 70 dB at Ka; > 70 at Q Ka ↔ Q > 70 dB at Ka; > 55 dB at Q
Peak Power	> 5.0 kW Multipaction
Size	6"(L) × 4" (W) × 4"(H)
Mass	< 500 g (flight network only)

Table 6. A summary of the measured performance of an ultra-compact Ku-band tracking feed.

Parameters	Measured Performance
Frequency	Ku-Band
Axial Ratio, On Axis	< 0.25 dB
Return Loss	> 24 dB
Isolation, Port to Port	> 30 dB
Null Depth	> 35 dB
Size	< 3.1" × 3.5" × 11.2"
Mass	< 3 lbs

Figure 16. An ultra-compact Ku-band tracking feed.

3.6 Ku-Band Tracking Feed

A low-profile tracking feed was successfully designed, built, and tested in a very short time. This feed included polarizers for generating circularly polarized signals, and hybrids for the monopulse comparator network. The challenge for this feed was to package all of these components in a cross section that was less than 3.1 in × 3.5 in. Four WR62 waveguide ports provided the desired circularly polarized sum and difference signals. As with most other feeds produced by CMI, no tuning screws were used. This feed was also built directly from design with no prototype or engineering unit, and is shown in Figure 16. A summary of the measured performance is listed in Table 6.

4. Conclusion

An integrated method that combines RF design, precision CAD, and precision electroforming to realize high-performance feeds for reflector antennas, without the need for prototyping and bench tuning, has been presented in this paper. Electroforming is used very effectively to eliminate joints, minimize piece parts, and realize complex features with tight tolerances. The resulting hardware provides very high RF performance, high power-handling capability, and ultra-low-passive-intermodulation performance, in a compact layout. Precision design and manufacturing eliminates the need for prototyping and bench tuning, which drastically reduces cost and schedule. CMI has successfully delivered a large number of complex feed assemblies for space applications to several satellite manufacturers and operators, including Boeing S&IS, Lockheed Martin, Space Systems Loral, Orbital Sciences Corp., Ball Aerospace, Harris, and JPL/NASA.

5. Acknowledgement

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