8-17-98

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Robert S. MacWright, Ph.D., Esq.*
* (Admitted in NY, NJ and the U.S. Patent and Trademark Office)
Executive Director

August 17, 1998

Dr. John C. Webber
Assistant Director
National Radio Astronomy Observatory
2015 Ivy Road, STE 219
Charlottesville, VA 229903

Re: Royalty-free license to the Crowe/Bishop Wave Guide Casting and Molding Technology

Dear Dr. Webber:

As you know, William Bishop, Thomas Crowe, and their colleagues at the University of Virginia ("UVA") have developed a new technology (the "Technology") for the fabrication of waveguides, horns and channels ("Devices"). It is expected that this Technology, which is described more fully in Attachment A, will provide significant cost advantages over the more traditional machining-based fabrication methods. UVA has assigned the Technology to the UVA Patent Foundation for protection and licensing.

Dr. Crowe has informed us that NRAO currently plans to build a millimeter wavelength telescope (the "Project,") which is more fully described in Attachment B, and that NRAO believes that the use of the Technology in the Project may be of considerable value to NRAO and its public service mission of radio astronomy. In consideration of the long-standing and ongoing research and scientific relationship between UVA and NRAO, the parties having an interest in the disposition of the Technology (UVA, and inventors William Bishop, Thomas Crowe, Jeffrey Hesler, Philip Koh, Robert Weikle, and Perry Wood) by their signatures below agree that the Patent Foundation should provide NRAO with a royalty-free, non-exclusive right and license under any patent, trade secret or other rights in and to the Technology, in order that NRAO may use the Technology in the Project; and by its signatures below, the Patent Foundation hereby grants such license to NRAO. This right and license shall expire upon the completion of the Project, but in no event shall NRAO thereafter be liable to make any payment for the continued use of Devices made during the term of such license.

The above-granted right and license is conditioned on NRAO's agreement to freely provide UVA, the Patent Foundation, and Mr. Bishop and Dr. Crowe with full and complete access to any and all information regarding NRAO's use of the Technology and Devices made thereby, including without limitation methods and procedures for the manufacture, installation, testing and use of Devices made using the Technology, and data demonstrating the functionality and performance of the resulting Devices. In addition, we ask that NRAO acknowledge the contributions of UVA and Mr. Bishop and Dr. Crowe as is academically appropriate in all publications and reports that NRAO may make. We also ask that should NRAO make one or more potentially patentable improvements on the Technology, that NRAO will inform the Patent Foundation of same, and will negotiate with the Patent Foundation to develop a joint marketing agreement through which the Patent Foundation and NRAO can jointly license their respective rights to industry, subject to the distribution of the proceeds in accordance with their respective contributions to the entirety of the rights so licensed.

Lastly, we ask that you consider the information provided in Attachment A and any other information that we provide you with regarding the Technology to be confidential, and that you not disclose same to third parties in publications or otherwise, or provide materials or prototypes to third parties, unless the Patent Foundation and Mr. Bishop and Dr. Crowe have consented to same in advance. UVA and Mr. Bishop and Dr. Crowe hereby agree to extend the same confidential treatment to information, materials and prototypes that NRAO may provide to them with respect to the Project or improvements NRAO may make in the Technology. Of course, neither party will be required to treat as confidential any information which is already publically known, information which is rightfully received from third parties, or information which they may independently develop without having had access to the other's confidential information. These confidentiality obligations with respect to specific information, prototypes or materials will expire three (3) years after first being provided to the receiving party.

We collectively hope that the grant of this right and license will advance the Project and thus contribute to your efforts to detect and understand radio signals emanating from space.

Sincerely,

Robert S. MacWright
Executive Director

Agreed and accepted by:

Inventors

Thomas Crowe

8/19/98

Date

Jeffrey Hesler

8/19/98

Date

Robert Weikle

8/19/98

Date

William Bishop

8/19/98

Date

Philip Koh

Date

Perry Wood

Date

University of Virginia

Office of the Vice Provost for Research

8/19/98

Date

National Radio Astronomy Observatory

Director

Date

University of Virginia Patent Foundation

Robert S. MacWright - Executive Director

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Haydn N.G. Wadley - President

Date

8-17-98/A

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Attachment A

Royalty-free License Agreement between UVAPF and NRAO
Copy of the provisional patent application for our reference *Bishop-Waveguide*

0494-222-2PROV
BISHOP ET AL.-WB03

This invention was made in part by funds provided by the U.S. Army Research Laboratory. The U.S. Government may therefor have certain rights in the invention.

TITLE OF THE INVENTION

Mastering, Molding and Casting (MMC) Technology
For High Precision Fabrication Of
Millimeter And Submillimeter Wavelength
Hollow Waveguides, Channels, Horns And Assemblies

CROSS REFERENCES TO RELATED APPLICATIONS

This application is related to United States Provisional Application Attorney Docket Number 494-220-2PROV by Koh et al entitled "INTEGRATION OF HOLLOW WAVEGUIDES, CHANNELS AND HORNS BY LITHOGRAPHIC AND ETCHING TECHNIQUES" filed March 25, 1997, and United States Provisional Application Attorney Docket Number 494-221-2PROV by Koh et al entitled "A PREFERENTIAL CRYSTAL ETCHING TECHNIQUE FOR THE FABRICATION OF MILLIMETER AND SUBMILLIMETER WAVELENGTH HORN ANTENNAS" filed March 25, 1997, both of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention:

This invention relates to the fabrication and reproduction of millimeter and submillimeter wavelength devices using mastering, molding and casting (MMC) techniques, and more particularly the fabrication of high precision millimeter and sub-millimeter wavelength hollow waveguides, channels, horns, and assemblies using MMC techniques.

Discussion of Background:

In general terms, an electromagnetic waveguide is any structure which is capable of confining and guiding electromagnetic energy from one point to another in a circuit. A variety of structures have been devised to accomplish this goal. For example, coplanar waveguide is a type of waveguide which consists of thin strips of coplanar conductive material on a dielectric substrate. Another example is dielectric waveguide in which the radiation is confined in a coaxial dielectric tube by the principle of total internal reflection. A hollow metal electromagnetic waveguide is an electrically conductive hollow tube or pipe-like structure or a collection of such structures designed to confine and guide electromagnetic radiation. Hollow metal waveguides are usually rectangular or circular in cross section. A horn is a tapered or flared waveguide structure which couples energy to or from free space within a defined spatial distribution (beam pattern). Only the inside surface of these structures must be conductive as the major fraction of the electrical current is constrained by nature to flow within a thickness known as the skin depth which is directly related to wavelength. Also the inner dimensions of such waveguides are determined by the radiation wavelength and are also generally proportional to wavelength.

Because of these relationships, the fabrication and design of hollow waveguide assemblies and components are strongly dependent on the operating wavelength. For example, in the case of microwaves with wavelengths on the order of centimeters, hollow waveguides can be easily fabricated by the extrusion of rectangular metallic tubes which have inside dimensions on the order of centimeters. Injection molded or extruded plastic waveguide components are also typically easily made for microwave wavelengths if they are coated with a sufficiently thick conductive material on internal surfaces. Also waveguide components for microwave frequencies can be made in sections which are joined by flanges and alignment is typically not difficult because of the relatively large dimensions.

However, the fabrication of hollow waveguide assemblies for millimeter and submillimeter wavelengths is typically much more difficult because the dimensions are correspondingly smaller. Also assemblies and subassemblies of waveguides sometimes include active electronic devices such as diodes or transistors and other passive components and circuits to make radio receiver and transmitter components such as heterodyne mixers. Therefore a complex network of accurately aligned, interconnected and very small hollow metal channels must be made and some of these channels must hold active and passive electronic components. This is generally not feasible with microwave style tubing.

A waveguide assembly designed for millimeter and submillimeter wavelengths is traditionally made by fabricating two machined metal "half" blocks, which when joined together, form a structure comprised of air-filled metal channels. Because of RF electromagnetic field and current considerations, it is rare that any of the slots can typically be formed only in one half with the other half being a simple flat cover. Thus the blocks have slots of various shapes and sizes which are often, but not always the mirror image of each other and which require precise control of depth, width and position (i.e., alignment). This "split block" approach solves two basic problems: (1) the difficulty of monolithically forming complex and very small hollow metallic structures and (2) the need to insert a circuit deep within the structure.

In recent years high quality millimeter and submillimeter wavelength components have been manufactured using the technique based on direct machining of metal blocks, for example, as described by Siegel et al., "Measurements on a 215 GHz Subharmonically

Pumped Waveguide Mixer Using Planar Back-to-Back Air-Bridge Schottky Diodes", IEEE Trans. Microwave Theory and Tech., Vol. MTT-41, No. 11, pp. 1913-1921, Nov. 1993, and Blundell et al., "Submillimeter Receivers for Radio Astronomy", Proc. IEEE, Vol. 80, No. 11, pp. 1702-1720, Nov. 1992. Figure 7 of Blundell et al is a drawing of a machined horn antenna and waveguide fabricated using the described split block technique. The primary benefits of machining the waveguide and the horn antenna into the metal block are that it is a well understood process which gives the designer great flexibility, the final structure is robust, and all internal components, such as semiconductor diodes, are protected. Another asset of traditional machining that is often taken for granted is its enormous dimensional depth range. Hole or slot depth can easily range from one mil to 1 inch (1:1000). This allows, for example, the formation of the relatively large holes required for the insertion and mounting of electrical connectors needed to move low frequency signals (IF, DC) to or from the waveguide block. The machining process is essentially three dimensional, and therefore allows the integration of electromagnetic horns of nearly arbitrary shape.

Although the above-described direct machining technique has gained wide industry acceptance, the expense of the required machining equipment, the personnel expertise, and the fabrication time greatly increase the cost of fabricating millimeter and submillimeter wavelength components. Also, as the desired operating frequency of the components is increased (i.e., wavelength is decreased), the required dimensions of the metal block features shrink proportionally in relation to the decrease in wavelength, making fabrication even more costly and difficult.

For example, another common technique for fabricating millimeter and submillimeter wavelength components is known as electroforming, for example, as described by Ellison et al., "Corrugated Feedhorns at Terahertz Frequencies-Preliminary Results", Fifth Intl. Space THz Tech. Symp., Ann Arbor, MI, pp. 851-860, May 1994. In the electroforming technique, a metal mandrel is formed by high precision machining methods and is then used as a metal core around which a second metal is deposited by electroplating. It is this second metal which eventually forms the hollow waveguide after the initial metal is chemically etched away. This technique is employed because it is often easier to machine the mandrel than the actual waveguide itself. Using this technique, components have been fabricated for frequencies up to 2.5 THz, however, the fabrication of the components is still costly and difficult.

Another technique for fabricating millimeter and submillimeter wavelength horn antennas is known as silicon micromachining, for example, as describe by Ali-Ahmad, "92 GHz Dual-Polarized Integrated Horn Antennas", IEEE Trans. Antennas and Prop., Vol. 39, pp. 820-825, July 1991, and Eleftheriades et al., "A 20 dB Quasi-Integrated Horn Antenna", IEEE Microwave and Guided Wave Letters, Vol. 2, pp. 73-75, Feb. 1992. Using this technique the horn antennas are fabricated using a preferential/selective wet etch and silicon wafers with a correct crystal orientation, such that the etch process proceeds very quickly in the vertical or (100) crystal plane direction but which virtually stops when the (111) crystal planes are reached. The etch is carried to completion such that only the (111) plane surfaces are exposed, and the result is a pyramidal shape etched into the silicon having a flare angle between two opposite sides of the pyramidal shape of about 70 degrees.

Another method of producing millimeter and submillimeter wavelength waveguides and horns involves the use of photoresist formers as described by Treen et al, "Terahertz Metal Pipe Waveguides", Proc. 18th Intl. Conf. on IR and Millimeter Waves, pp. 470-471, Sept. 1993, Brown et al, "Micromachining of Terahertz Waveguide Components with Integrated Active Devices", Proc. 19th Intl. Conf. on IR and Millimeter Waves, pp. 359-360, Oct. 1994, and Lucyszyn et al, "0.1 THz Rectangular Waveguides on GaAs Semi-Insulating Substrate", Electronic Letters, Vol. 31, No. 9, pp. 721-722, April 1995. Techniques using photoresist formers to fabricate waveguides and horns take advantage of processing developed by the silicon microelectronics industry. Using this technique, hollow waveguides and horns formed around appropriately shaped layers of photoresist have been fabricated. The benefit is that the processing and shaping of photoresist is a well developed technology which can be precisely controlled on large wafers, thereby allowing many structures to be manufactured simultaneously and thus reducing costs. Also, photolithography easily provides the precision necessary for waveguide structures at the highest frequencies envisioned. The primary problems have been: (1) forming and processing tall enough photoresist structures cheaply and reliably, (2) removing the thick photoresist from inside the waveguides, and (3) producing horns which flare in two dimensions.

All waveguide assembly fabrication techniques which rely on micromachining, or photoresist technology suffer from several fundamental limitations: (1) The maximum depth of features is limited to several millimeters because of limitations in photoresist thickness due to light absorption or deposition quality or by limitations in practical etch rates; (2) Many of these structures are composite in nature with two or more materials being utilized. This can result in problems such as thermal expansion mismatch and processing incompatibilities; (3) The shape of channels is limited by the etching mechanism which is employed and by crystallographic effects. Arbitrary shapes are generally not possible, especially in different directions on the same wafer. For example, channels with a semicircular cross section which are required in some very efficient waveguide feed horn designs (e.g., corrugated horns) are not currently possible; (4) Additional structures must be provided to build a complete receiver component (e.g., mixer, doubler, etc) such as those required to protect delicate components and structures and to enable mounting and connection of other system components (e.g., SMA connectors); and (5) the production rate of micromachined waveguides can be severely limited by the number of waveguides which may be formed on a wafer and the number and complexity of the processing steps which must be carried out. This problem increases as operating frequency decreases due to the increase in wavelength and corresponding increase in the size of the components.

SUMMARY OF THE INVENTION

Accordingly, one object of this invention is to provide a technique for the fabrication of millimeter and submillimeter wavelength structures which reduces the cost of fabricating the structures.

Another object of the present invention to provide a technique for the fabrication of millimeter and submillimeter wavelength horn antennas integrated with waveguides, channels, and other components.

Another object of the present invention to provide a technique for the fabrication of millimeter and submillimeter wavelength horn antennas integrated with waveguides, channels, and other components wherein high precision machining is greatly reduced thereby reducing component and system costs.

Another object of the present invention to provide a technique for the fabrication of millimeter and submillimeter wavelength horn antennas integrated with waveguides, channels, and other components wherein thermal expansion mismatch and processing incompatibilities are minimized or reduced.

Another object of the present invention to provide a technique for the fabrication of millimeter and submillimeter wavelength horn antennas integrated with waveguides, channels, and other components which facilitates fabrication of complete components, such as mixers with additional structures to build a complete receiver component (e.g., mixer, doubler, etc), components required to protect delicate devices and structures, and structures to enable mounting and connection of other system components (e.g., SMA connectors).

Another object of the present invention to provide a technique for the fabrication of millimeter and submillimeter wavelength horn antennas integrated with waveguides, channels, and other components with increased production rate.

The above and other objects are achieved according to the present invention by providing a new and improved method of fabricating a millimeter or submillimeter wavelength device including forming a master of the millimeter or submillimeter wavelength component, forming at least one mold from the master, and forming at least one replica of the millimeter or submillimeter device using the mold.

According to a further aspect of the present invention, the master is formed by machining or otherwise forming channels, grooves and connector ports into a millimeter or submillimeter wavelength component block, rounding the edges and tapering the sides of the device block, providing a backshort in a channel of the millimeter or submillimeter wavelength component block, and by providing a thin coating layer for surface protection and mold release.

According to another aspect of the present invention, the mold is formed by providing a cavity with a baseplate which is attached to the master and pouring a mold resin into the cavity surrounding the master. The mold is cured and the master is extracted from the cured mold resin. According to another aspect of the invention, a liquid casting resin is poured into the mold and around the master. The casting resin is cured to form a solid replica of the master and this solid replica is removed from the mold.

According to yet another aspect of the present invention, a metalization layer is then added to the working surfaces of the replica and two replicas, which are designed to be combined are joined so as to form a complete a millimeter or submillimeter device.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed descriptions when considered in connection with the accompanying drawings, wherein:

FIG. 1 is a top right perspective view showing the reproduction of millimeter and submillimeter wavelength devices using mastering, molding and casting (MMC) techniques, according to the present invention;

FIGs. 2A-2D are views showing mastering techniques, according to the present invention;

FIGs. 3A-3D are views showing backshorting techniques, according to the present invention;

FIGs. 4A-4G are views showing composite mastering techniques, according to the present invention;

FIGs. 5A-5B are views showing the use of thin films to protect and to impart release properties to various composite materials in mastering techniques, according to the present invention;

FIGs. 6A-6B are views showing a mold fixture assembly, according to the present invention;

FIG. 7A-7B are views showing backside forming options, according to the present invention;

FIG. 8A-8F are views showing a mold fabrication process, according to the present invention; and

FIG. 9A-9H are views showing a casting process, according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, wherein like reference numerals designate identical or corresponding parts throughout the several views, and more particularly to Figure 1 thereof, there is illustrated a process for reproduction of millimeter or submillimeter wavelength devices using mastering, molding and casting (MMC).

In Figure 1, a master device 2 of a millimeter or submillimeter wavelength device, for example, formed by traditional machining or by any other suitable process or combination of processes, such as micromachining, preferential etching, etc., as previously discussed, can be made of any suitable material. The present invention uses novel MMC techniques to drastically reduce the cost of fabricating millimeter and submillimeter wavelength components, such as mixers, multipliers, or housings fabricated using the above-described methods, or techniques described, for example, in Hesler et al, "Fixed Tuned Submillimeter

Wavelength Mixers Using Planar Schottky Barrier Diodes", IEEE Trans. Microwave Theory and Tech., Vol. 45, No. 5, May 1997, or United States Provisional Application Attorney Docket Number 494-221-2PROV filed March 25, 1997, by Koh et al entitled "A Preferential Crystal Etching Technique for the Fabrication of Millimeter and Submillimeter Wavelength Horn Antennas", both of which are incorporated herein by reference. A mold 20 corresponding to the master 2, is fabricated using any suitable material which can be formed around the master 2, yields high dimensional reliability upon release from the master 2, and is suitably durable. Final replicas 30 corresponding to the master 2 and made from the mold 20 can also be made of any of a variety of suitable materials. One criteria being that the final replicas 30 can be formed in the mold 20, maintain etch dimensional reliability, and are suitably durable for the lifetime of the final component. As a final step of the process the cast structures of the replicas 30 are coated with a suitable material to achieve low loss surfaces.

A detailed description of the MMC techniques according to the present invention will now be described with reference to Figures 1-9. Molding and casting is an ancient art regarded as a means for replication of simple objects. However, given an optimal combination of mastering, molding and casting according to the present invention, high precision millimeter and submillimeter wavelength assemblies (also referred to as "waveguide assemblies") which exhibit improved quality and/or lower manufacturing cost can be fabricated as compared to traditional machining, such as micromachining, preferential etching, etc., as previously discussed. According to the present invention, the molding and casting portion of the process is strongly coupled to the mastering portion in terms of the geometrical layout, the choice of materials and the specific techniques which are employed which distinguishes the present technique from traditional casting/molding methods. The masters which are used in the present invention are typically unique to the process according to the present invention, but other waveguide techniques may also be used in combination to fabricate the masters.

Fabrication of millimeter and submillimeter wavelength components/assemblies by MMC according to the present invention drastically alters the economics of manufacturing such devices since only one master block pair must be made for each millimeter or submillimeter wavelength design. Costly and time-consuming fabrication techniques and enhancements which are prohibitive in non-replicative manufacturing become economically feasible even for high production levels. Thus both the quality and the quality/cost ratio of a replicated millimeter and submillimeter wavelength components/assemblies may be better than that of a traditional machined millimeter and submillimeter component. For example, the use of quality enhancing methods such as very low machining feed rates, electropolishing, electroplating, state-of-the art computer numerically controlled (CNC) machines, and interferometrically controlled tool positioning become economically viable.

Mastering

Hollow waveguide assemblies for millimeter or submillimeter wavelengths can be ideal candidates for fabrication by means of the MMC technology of the present invention. However, the master block 2 must typically be designed to take maximum advantage of the molding and casting materials and techniques of the invention. One consideration is to minimize the detrimental effects of demolding (removing either the master 2 or the cast replica 30 from the mold 20). This step puts stress on the mold 20 and can cause it to become distorted, to tear or to break. Since millimeter and submillimeter wavelength structures require dimensional control on a scale as small as several microns, this damage cannot be typically tolerated. This concern is overcome in the present invention in several ways, the first of which is the selection of a modified form of open cavity molding which is unique to the invention. According to the present invention, casting resin is poured into an open cavity mold 20, that is, a mold which is in essence an open box shape. This leaves the open face of the mold 20 as an access port for demolding the finished solid casting replica 30. However, this access alone does not eliminate demolding stress or damage. Such stress or damage is minimized in the present invention by one or more of the following features of the master block 2, used in fabricating the mold 20, which typically have no effect on the performance of the finished waveguide assembly as will now be discussed.

No waveguide assembly feature which would require an expansion or stretching of the mold can be tolerated. In practical terms, this means that features may certainly and preferably be defined in the bottom face of the open cavity. Features may be defined in the sidewalls but only with lines, ridges or recesses which run perpendicular to the bottom or those which are not isolated from the waveguide face. In Figure 2A, this above restriction is illustrated in the requirement for an electrical connection port 2a in the millimeter or submillimeter wavelength assemblies master block 2 (i.e., SMA connector 2a). In a typical machined block 2, for example, as described by Hesler et al, having a diagonal horn 2b, a waveguide 2c, DC bias slot 2d, and channel structure 2e (e.g., mixer circuit probe slot), this port 2a would be located precisely and drilled through one of the block halves as shown in Figure 2A. Notice that the hole 2a is drilled perpendicular to the plane of the channel structure 2e and it is stepped in diameter being larger on the back side than on the channel structure 2e side. A mold 20 made from such a master block 2 could not be separated from its master 2 without severe stress and distortion of the mold 20. While it may be possible to form the inner portion of this port 2a in the casting and then drill through the back of the replica 30 to meet it, it is much more preferable to form the SMA port 2a as illustrated, for example, in Figure 2b. In Figure 2B, half of the SMA port 2a is machined into each block half 2 in a location and with a shape which does not put any undo stress on the mold 20.

In addition, alignment features 2f' and 2f' could be machined in area 2f. By using alignment features 2f' and 2f' on both half block masters in the form of aligned slots, the block halves can then be forced into alignment by placing one or more short (as compared to slot length), snugly fitting rectangular bars into place, each of which spans between the slots. Thus alignment is simplified as compared to a peg and hole alignment feature since it is typically more difficult to align drill holes than it is to align intersecting slots with intersecting bars as in the present invention.

In addition to the above master block 2 design considerations, the vertical edges 2h of the master block 2 of Figure 2A and 2B can be rounded as shown in 2h' of Figure 2C, since sharp edges 2h will cause stress concentration in the mold 20 itself and the corresponding sharp edges 2h in the master block 2 and in the cast replica 30 are more likely to cut the mold 20. Further, the mold 20 release characteristics can be enhanced by introducing a taper 2i, for example of greater than three degrees (no specific taper minimum has been established), in the sidewalls of the master block 2 (i.e., the patterned face of the master block 2 which forms the bottom of the open cavity mold 20 is smaller in width and length than the corresponding dimensions of the opposite face), as illustrated in Figure 2D. In the preferred embodiment, the back side of the master block 2 will be provided with a blind threaded hole (not shown) which is used to mount the master to the mounting fixture baseplate and which serves as a gripping point to enable the removal of the master from the mold.

The materials used to fabricate the master block 2 in the present invention can be very different from those used to make "single use" or "direct use" traditional waveguide assembly since the only important characteristic is typically the final shape of the master block 2. Within fairly wide limits, factors, for example, such as the master block 2 material strength, hardness, and electrical and thermal conductivity, are typically unimportant. Thus materials with exceptionally good machining or other processing properties, but which are otherwise unsuitable for "direct use" blocks may make excellent replication master blocks 2.

Another feature of the present invention is the use of multiple or composite material structures to form the master block 2. A good example of the utility of the composite master concept, according to the present invention, is the "backshort" structure which is typically necessary in most mixer designs. A backshort is a blind slot which is used to reflect radiation back into the waveguide 2c to create a desirable standing wave pattern to improve energy coupling to the mixer element. Thus backshort position is typically critical and is used as a tuning device. However, blind rectangular slots with flat, vertical end walls are virtually impossible to make with traditional machining techniques (i.e., milling, scraping, drilling, turning). The backshort structures are thus typically formed by filling in a slot at some point with a separate block of metal which may be held in place by a tight fit or other means in the waveguide 2c. Sometimes backshort structures are created by pushing a soft metal such as indium into an existing slot as taught by Hesler et al. Note in this case the final waveguide is a composite structure with one relatively weak, very low melting point component.

However, a backshort structure according to the MMC technology of the present invention can be made of a metal or a non-metal since only its physical characteristics are important. In Figure 3B, for example, a plastic plug 2c' with a rectangular cross section is pressed into the waveguide slot 2c of Figure 3A in a position where the backshort is desired. The cast replication of this composite master block 2 would be a mold 20 with a monolithic backshorted slot 2c'', as shown in Figure 3C. The plastic plug 2c' could be removed and repositioned at will in the master block 2. This would allow one machined master block 2 to produce a variety of composite molds 20 as shown in Figure 3C and replicas 30 as shown in Figure 3D, each with a different backshort position. This would greatly improve the quality, performance and reduce the cost of the waveguide mixers and other devices requiring a backshort. A composite backshorted slot could also be made by filling the entire slot with a photopolymer which cures on exposure to light. By means of highly accurate photolithographic techniques, a specific section of the slot can be left with a polymer "plug" with very straight sidewalls. The replication of this structure would obviously be monolithic. In addition, if the master block 2 is made of chemical resistant material, then the photopolymer backshort could be chemically removed and replaced at will, thus again allowing the fabrication of components with a variety of backshort positions from one machined master block 2.

Another example of the utility of a composite master concerns the wide range of dimensions involved in waveguide component fabrication. A horn antenna section can start with dimensions on the order of several millimeters and taper down to a rectangular waveguide slot which is only 0.1 millimeters. The large features of the horn are typically easy to make with high quality CNC machining but the small features are difficult. Moreover, the pattern of "machine marks" or scratches which are inherent in machining create relatively large non-uniformities in the small slots. Misalignment of the small slots should be kept below ten percent which may be less than 10 microns. Thus it would be desirable to make a composite master in which the horn is made by one relatively "coarse" technique such as traditional machining, and the slots by a relatively "fine" technique such as photolithography. Other composite techniques such as that described by Koh et al, "Integration of Hollow Waveguides, Channels and Horns by Lithographic and Etching Techniques", incorporated herein by reference, may be useful in forming casting master blocks 2 either alone or in combination with other methods.

In the embodiment as shown in Figures 4A-F, a metal master block 2 is ground flat on one side (Fig. 4A) and has a region 2f milled (Fig. 4B) out to prevent unnecessary interference in joining the block halves and also provide a recess to accept the small waveguide slots. The connector port 2a is machined (Fig. 4C), and a diagonal horn slot 2b (Fig. 4D) is next formed from one edge to the milled-out recess 2f in such a manner that the horn slot breaks through the recess edge where its height is equal to the recess depth. The recess is next filled in with a photopolymer or photoresist 2k (Fig. 4E), such as photosensitized Shell SU-8 and the photopolymer 2k is patterned photolithographically to form the small waveguide channels 2c, 2d and 2e (Fig. 4F) which intersect the horn 2b and to form other required slots. Miniature alignment features could also be formed in this step as taught by Koh et al, "Integration of Hollow Waveguides, Channels and Horns by Lithographic and Etching Techniques", incorporated herein by reference.

Another alternative is to form the small waveguide channels by the following method. As shown in Figure 4G, the step of Figure 4E above could be skipped and a small waveguide circuit 21 comprised of a carrier such as silicon can be made using photolithography to accurately define rectangular channels 2a, 2b, and 2e in a photopolymer. This circuit 21 can be bonded in position such that (1) its top surface is coplanar with the topmost surface of the machined master block 2 and also so that the appropriate waveguide channel 2c is closely connected to the diagonal horn 2b.

Some master block 2 materials, shown in Figure 5A, may have a tendency to bond or react with the mold material (e.g., silicone, polyurethane). Traditional mold release coatings, such as waxes and sprays are typically unsuitable in fabricating millimeter or submillimeter wavelength devices since they are so thick they alter the device dimensions. However, the deposition of a very thin (<1000 A) of metal, ceramic or polymer, shown as 2j in Figure 5B, can provide a master block 2 surface protection and mold 20 release enhancements without significantly affecting the waveguide dimensions. Common thin film deposition techniques such as evaporation, sputtering or vapor/plasma deposition can be used to deposit the thin film release/protection layer 2j. These release/protection layers 2j can usually completely eliminate any incompatibilities or adhesion between the molding resin and the master block 2 material, especially in the case of composite master blocks 2 where one material may be delicate or reactive. This technique, according to the present invention, further expands the possibilities for materials for the master block 2 fabrication.

Molding

The mold resin which is used to fabricate molds according to the present invention can typically be made from a variety of polymeric materials, such as silicone rubber or polyurethane. Both silicone rubber and polyurethane have excellent fidelity. However, a hard RTV silicone rubber is preferable for mold 20 fabrication according to the present invention since this material combines excellent detail reproducing capability with excellent mold release characteristics. Bubble elimination using a simple vacuum treatment in the mold 20 is much more effective and complete with silicone rubber as compared to polyurethanes. Polyurethanes are more difficult to "degas" which leaves small voids in the mold 20 which typically can be devastating to the ultimate replication. Desirable properties for silicone compounds for mold 20 fabrication according to the present invention include: (1) silicone RTV (room temperature vulcanizing) rubber which either fully cures at room temperature with low shrinkage (<1%) or which can be cured before demolding or postcured (after demolding) at elevated temperatures without excessive shrinkage, stress or distortion of the pattern; (2) addition cured rather than condensation cured for best inhibition resistance and complete thick section cure with typically no reaction by-products; (3) hardness preferably in the relatively high range for this type of material (Shore A >40); and (4) other properties typical of silicone rubber designed for molding such as high tear resistance and good release characteristics without the use of mold release agents.

A molding/casting fixture 100 according to the present invention is shown in Figure 6A and 6B. The molding fixture 100 holds the master block 2 in a fixed and centered position and provides confinement of the liquid molding resin. In the embodiment shown, the molding fixture 100 includes a cylindrical confinement/support ring 4 used for confinement which, after curing of the silicone resin, remains bonded to the rubber. This helps to maintain the global shape of the master block 2 and prevents distortion during use. The cylindrical confinement/support ring 4 can be made from low cost standard tubing which is simply cut to length and has its ends faced flat and smooth in a lathe. The confinement ring can be made of any material which is compatible with the mold resin but is preferably made of a material with a coefficient of thermal expansion which closely matches that of the mold material. The outside or inside diameter of the confinement/support ring 4 is typically not critical, but the length should be greater than the master block 2 height and may allow space for the reinforcing plate 12 and screws 12b. The reinforcing plate 12 and/or screws 12b is not necessary but may be included. To improve the bond between the confinement/support ring 4 and the mold resin, the inner surface must be clean and it may additionally be scored, sanded, scratched or grooved although this will increase its cost. Aluminum is an ideal molding fixture 100 material (with the exception of the confinement/support ring 4 and rear reinforcing plate 12 and screws 12b which preferably should be made of a material with a thermal expansion coefficient which is relatively close to that of the silicone rubber molding compound) since it is low cost, easy to machine and does not inhibit silicone rubber curing.

As shown in Figures 6A and 6B, the molding fixture 100 includes a baseplate 6 which holds the master block 2, via master attachment screw 16, in position and which holds the above cylindrical confinement/support ring 4 in a centered position with respect to the master block 2, an o-ring seal 8 between the baseplate 6 and the confinement/support ring 4 and a clamping means 10, such as bolts and nuts 10a, to hold the confinement/support ring 4 tightly sealed to the baseplate 6. A rear reinforcing plate 12, although not necessary, is typically in the form of a circular disk which includes tapped thru-holes 12a distributed in a radial pattern is provided opposite the baseplate 6. Machine screws 12b of the appropriate length are screwed into some of the tapped holes 12a so that the screw heads 12c will be embedded into the silicone rubber thereby locking the reinforcing plate 12 and screws 12b in place and reinforcing the mold 20. A hard connection can also be made with screws through untapped holes at the edge of the reinforcing plate 12 and into matching tapped holes in the edge of the confinement/support ring 4. The rear reinforcing plate 12 can be made in a variety of ways to include the essential feature of reinforcing the silicon rubber as much as possible.

As further shown in Figure 6A, the molding fixture 100 also includes a removable overflow tube 14 made of clear or opaque plastic or metal positioned in such a manner as to extend the confinement/support ring 4 and allow for the temporary volume expansion caused by the vacuum "degassing" process in which the silicone rubber "rises" or "foams" as entrapped air is removed.

Casting

Casting resin for replication of the waveguide assemblies in a variety of very hard (> Shore D 60) thermoset polymers such as polyurethanes, epoxies, and allylics for which cure may be initiated by the mixing of a catalyst, or the application of heat or radiation, including UV light is used. Important properties of the casting resin include: (1) uncured resin which has low viscosity, long pot life, bubble free or easy bubble elimination, simple mixing or single component, low temperature cure, and simple curing process; and (2) cured resin which has good release characteristics, very low shrinkage, excellent mechanical and thermal properties, and good machinability.

As shown in Figure 7a, the mold 20 design includes a backside former 18. Open cavity molds typically form a solid object with five controlled surfaces. The shape of the sixth surface, the "open" side of the mold, is normally controlled only by surface tension and gravity (level). The back side of a replica block which is cast in a simple open cavity mold will not be flat but rather concave or convex. Thus additional machining is required after demolding if a flat rear replica block 30 surface is desired. In addition, removal of the cast replica block 30 will be difficult and will require the use of either some sort of prying tool or drill and tap procedures which may damage the part and/or distort the mold 20. A unique solution to both of these problem according to the present invention is to include a "back-side former" 18 as shown in Figure 7a. In Figure 7a, the "back-side former" 18 is comprised of a relatively flat disk with a centering lip 18a or other centering means around the perimeter and a tapped hole 18b in the center. A machine screw 18c is threaded through the tapped hole 18b and extends below the inside disk surface. The inside surface and protruding screw 18c threads are coated with a conventional mold release (wax, Teflon spray). When the back-side former 18 is positioned on the open cavity mold 20 over confinement/support ring 4, the screw 18c is suspended in the center of the mold 20 cavity 22 and is embedded in the cast waveguide replica block resin. The back-side former 18 can be made of various materials including a plastic Petri dish top whose edge acts as a centering lip 18a (if the confinement/support ring 4 is appropriately sized) and which are very low cost (disposable) and transparent. A hole 18b is drilled through and tapped for a small screw 18c (e.g., 10-24) in the back-side former 18. After filling the mold 20 cavity 22 with liquid casting resin 20a, the back-side former 18, with center screw 18c is lowered onto the mold 20. As the back-side former 18 is lowered, the screw 18c displaces a small quantity of resin and the level of resin rises slightly above the top surface of the cavity 22. This excess resin then contacts the inner surface of the back-side former 18 and is spread out to the perimeter of the mold confinement/support ring 4. This procedure simultaneously flattens the back side of the cast replica block 30 and embeds a release-coated screw in the replica block 30. After the resin cures, the embedded screw 18c is first removed by unthreading and then the back-side former 18 disk is pulled off (it releases easily because of a wax/Teflon coating). The screw 18c (or another screw with the same thread pattern) is now threaded into the cast-formed threaded hole in the replica block 30 in such a manner as to leave exposed a sufficient length of the screw 18c to serve as a gripping support for demolding. Demolding can be accomplished "by hand" by pulling on this screw 18c or by prying against the underside of the screw 18c head using the edge of the confinement/support ring 4 as a fulcrum. A replica block "puller" (not shown) utilizing a threaded hole in the replica block in a similar manner as described above can also be employed. The replica block puller, if employed, exerts force precisely perpendicular to the open face of the mold 20 and supports the silicone rubber against distortion from the demolding action by providing a rigid plate with an aperture just slightly larger than and concentric to the opening of the mold 20 cavity 22.

An alternative to the above-described "backside former" is the "backside insert" 17 as shown in Figure 7B. The backside insert 17 is a solid block which is designed to be positioned inside the mold cavity 22 and to be permanently bonded to the casting resin. This backside insert 17 can be made of plastic or metal which is compatible with the casting resin. This backside insert 17 is designed to displace most of the mold cavity 22 volume thereby creating a finished waveguide component in which the geometrical features formed by the mold 20 are contained in a relatively thin section of the casting resin. The backside insert 17 can be a simple shape or it may be a preformed part, ideally a low cost injection molded plastic or metal casting in which non-critical features (such as holes for mounting and demolding or connector ports) have been pre-formed at very low cost. If the backside insert 17 is transparent plastic, then a light or ultraviolet-curing casting resin could be used. These resins cannot typically be used to form a full thickness replica block 30 since efficient curing is limited to thin sections because of light/UV absorption. The use of light or UV activated curing has the advantages of unlimited "pot" lifetime, very short cure times and generally are provided as single component systems. The elimination of resin component mixing increases production efficiency and reduces air bubble formation. This backside insert 17 also reduces the consumption of expensive casting resin.

Metalization

According to the present invention, the completed replica 30 waveguide assembly is typically coated with a, more or less, continuous layer of conductive material. This layer provides electrical conductivity and also provides other desirable functionality including protection (hermiticity) of the underlying polymer or other metals from chemical attack by intentional or unintentional exposure, protection of the underlying polymer from changes induced by absorption of water or other agents, the prevention of outgassing of organic vapors or moisture from the underlying polymer and good bonding qualities for soldering or wire bonding. This conductive coating, typically a metal coating, must exhibit high adhesion and resistance to peeling during abrasion or thermal cycling. Several excellent metal coating methods are available including evaporation, sputtering, chemical vapor deposition, electroplating and electroless plating. Electroless plating offers excellent hermiticity since the process deposits metal on all exposed surfaces including reentrant features such as pits and some holes. In practice, plastics are usually coated with two or more metals, the first to promote adhesion and the others to provide protection and high electrical conductivity. These coatings and processes are well developed and highly effective.

Details of the mold fabrication and casting of replicas will now be discussed with reference to Figure 8 and 9.

Mold Fabrication

In Figure 8A-8F, the mold resin 20a used for fabricating the mold 20 according to the present invention is, for example, a silicone compound 16-270 manufactured by Precision Silicones, Inc. This is an addition cured resin which cures fully at room temperature in 6-7 hours. It has a viscosity of 30,000 cps which is low for resins of this type and cures to a hardness of Shore A 55.

The mold fabrication process begins with thoroughly cleaning and drying parts of the mold fixture 100 and any mixing utensils which come into contact with the silicone rubber resin 20a. The master block 2 is coated with a layer of hydrofluorcarbon in a CHF3 plasma although other release layers could be used. Note that this release layer may not be necessary in all cases.

The master block 2 is fastened to the mold fixture 100 baseplate 6 with a center screw 16. The o-ring 8 is positioned in the baseplate 6 and the confinement/support ring 4 is placed into position on the baseplate 6 and around the master block 2. The mold fixture 100 clamp 10 is positioned on the confinement/support ring 4 and clamped tightly to the baseplate 6 with clamp bolts 10a. The reinforcing screws 12b are placed in position on the reinforcing plate 12. The silicone RTV resin system (PSI 16-270) is thoroughly mixed A:B::10:1 by weight in a glass beaker. A small quantity of the resin 20a is poured into the mold fixture 100 to cover the master 2 as shown in Figure 8A. The overflow tube 14 is placed atop the confinement/support ring 4 as shown in Figure 8B. The fixture with resin 20a is placed into a vacuum chamber and the pressure is reduced to 28-29 inches Hg and held at this level. Entrapped air will expand causing the resin mixture 20a to "foam" and expand in total volume and after several minutes this air will break free of the mass of the resin 20a and the level will drop. The vacuum is held for about one minute after this to ensure that all entrapped air has been released. The vacuum chamber is vented and the assembly is removed. More resin 20a is added and the procedure is repeated until the mold cavity 22 is completely full as shown in Figure 8C.

In Figure 8D, the rear reinforcing plate 12 with reinforcing screws 12b attached is positioned on the confinement/support ring 4 so that the screws 12b are embedded in the silicone resin 20a. The mold fixture assembly 100 is again placed in a vacuum chamber and the pressure is reduced to 28-29" Hg. After several minutes, entrapped air will be expelled and the assembly is removed from the chamber. The silicone-filled mold cavity 22 is left undisturbed for at least 12 hours at room temperature. In Figure 8E, the screw 16 which attaches the master block 2 to the baseplate 6 is removed. The fixture clamp 10 is released and the confinement/support ring 4, with cured resin 20a and embedded master block 2 is pulled away from the baseplate 6 as shown in Figure 8E. In Figure 8F, the master block 2 attachment screw 16 is then inserted directly into the master block 2 (bottom) and is used as a point to exert force to remove the master block 2. Typically, the master block 2 is easily removed with a moderate force applied to this screw 16. The mold cavity 22 is next inspected with a low power stereo and high magnification microscopes for defects in comparison to the master block 2. The mold 20 is stored in a dust-free environment or is covered at all time with a dust cover.

Replication By Casting

Replication by casting according to the present invention will now be described with reference to Figures 9A-9H. An excellent casting material is Conap Conathane UC-40 polyurethane. It has very low viscosity (500 cps) and a relatively long pot life (for PUR) of 14 minutes. It cures at room temperature with a linear shrinkage which is not measurable and a final shrinkage after heat cure of only 0.03 percent and can be demolded in 6 hours. Final cure is achieved in 16 additional hours at 80 C. The final cured polymer is hard (Shore D 75), strong (6900 PSI), moderate elongation (10%), high impact strength (Izod Unnotched 1.56 Ft-lb/in), and it has excellent machinability.

The casting process begins with mixing component cleaning. PUR's are highly moisture sensitive in the liquid state and thus should contact only dry, non-porous surfaces. Contamination of the liquid PUR resin can result in cure inhibition and/or a reduction in material properties. For these reasons, the mixing container must be clean and dry.

When the back-side former 18 is put into place some excess resin 24 is extruded from the cavity 22 and it can flow beyond the silicone rubber and contact the confinement/support ring 4 edge or outside. If the resin 24 bonds well to these surfaces, the back-side former 18 may be impossible to remove. To prevent this problem, all exposed surfaces of the confinement/support ring 4 and the reinforcing plate 12 must be coated with a mold release agent. However, such coatings must not be allowed to contact the inside of the mold cavity 22 since such coatings generally are relatively thick compared to the fine features of the mold 20. A practical method is to simply cover the cavity 22 with a solid disk which is larger than the cavity 22 diagonal but smaller than the confinement/support ring 4 diameter. The entire exterior of the mold assembly 20 is then sprayed with mold release (e.g., Teflon) and allowed to dry. Ideally this release spray cover is designed with an o-ring seal to contact the silicone rubber on the top surface of the mold 20 to prevent any possible leakage of the airborne release spray into the mold cavity 22.

Two-component polyurethane casting resins must be mixed just prior to use since pot lifetimes are generally short (<20 min). Conap UC-40 resin components are thoroughly mixed in a glass beaker with a glass stirring rod in an A:B::2:1 weight ratio. The PUR liquid casting resin 24 is poured into the mold cavity 22 to just cover the waveguide assemblies features 28 as shown in Figure 9A. In virtually all cases some small air bubbles will be trapped in contact with the silicone mold 20 surface 26. Some may originate from the resin 24 mixing process and some may be the result of entrapment of air as the liquid resin 24 is introduced. A relatively small number of bubbles in the bulk of the resin 24 (i.e., not in contact with the mold surface 26) may not be harmful to the cast replica block 30 physical properties (e.g., strength) unless they are very large. However, bubbles which are left in contact with the mold surface 26 can remain as the resin 24 cures to a solid thus forming voids in the active surface 28 of the waveguide replica block 30. Because of the very small feature size of the waveguide assembly design, air bubble voids must typically be totally eliminated, at least from the waveguide channels 2c, 2d and 2e shown in Figure 2. Air bubble elimination can be accomplished and aided by several techniques such as brushing with a very fine (#000) artist or spotting brush. However this is very labor intensive. Less labor intensive methods include vibrating the mold assembly 20, reducing the atmospheric pressure (vacuum degassing), increasing the atmospheric pressure and centrifuging or various combinations of these methods. Centrifugation, alone, of the partially or completely filled mold with the bottom surface of the mold perpendicular to the radius of the centrifuge (i.e., parallel to the bottom surface of the centrifuge rotor bucket) has been found to be the most effective and efficient method of bubble elimination in this process where polyurethane casting resins are employed. Additional resin 24 is poured into the mold 20 and any air bubbles are again eliminated. This process is repeated several times until the mold cavity 22 is completely full with resin 24 as shown in Figure 9B. It may also be possible to utilize only one resin 24 pour followed by air bubble elimination.

Once the mold cavity 22 is completely filled with liquid PUR resin 24 the back-side former 18 plate is gently lowered onto the mold assembly 20. It may be necessary to first apply a small quantity of resin 24 to the center of the screw 18c to provide sufficient excess resin. Alternatively, the mold cavity 22 may be slightly overfilled with surface tension preventing overflow and causing a slightly convex liquid resin surface 24a (Figure 9B). The back-side former 18 is finally pushed against the mold 20 as shown in Figure 9C. The mold assembly 20 is allowed to cure undisturbed at room temperature for at least 12 hours. If the mold confinement ring 4 is made of a material which nearly matches the mold resin 24 in thermal expansion coefficient, then the casting may be cured at elevated temperature (typically 80 C) for a much shorter time (typically 2 hours) prior to demolding.

In order to demold the replica block 30, the back-side former 18 screw 18c is unthreaded and removed and the back-side former 18 is pulled or peeled away from the mold 20 as shown in Figure 9D. Excess cured PUR resin 24b as shown in Figure 9E can next be easily peeled from the mold 20. A very thin film of cured resin 24b is formed in the backside forming process because of the inevitable gap between the former 18 surface and the mold 20. However, this film 24b is easily stripped away and it breaks cleanly and parts from the cast waveguide replica block 30 as shown in Figure 9F. The screw 18 is rethreaded into the formed threads 18d in the cast replica block 30 as shown in Figure 9G. This screw 18c is used as a gripping point to exert a force to remove the cast replica block 30 from the mold 20 (demold) as shown In Figure 9H. This can be done manually or with a "block puller" as described above. The room temperature cured replica block 30 is placed into a convection oven and the temperature is ramped up to 80 Celsius and held at that temperature for at least 16 hours and is then allowed to cool down to room temperature.

The cast solid PUR replica block 30 half may optionally cleaned with trichloroethane or other cleaning agents and blown dry with nitrogen. Next the replica block 30 may also optionally be treated with oxygen plasma at high pressure and low power (1T, 50 W) for a total of one hour. This process chemically etches away a thin layer of PUR and removes surface contamination and dulls any glossy surface with pits which are much smaller than the waveguide features. This dry etching process is generally believed to improve the adhesion of subsequent metals which are applied to the surface. The replica block 30 is next loaded into a vacuum sputtering system for metal deposition. This system must apply the metals over a wide range of incident angles to completely cover all recesses in the replica block 30a surfaces. This can typically be done by aiming the source towards the replica block 30 at typically 45 degrees from normal and rotating the replica block 30. Chromium, for example, is first deposited as an adhesion layer to a thickness of typically 50 to 200 A. This is followed by, for example, gold as a plating seed layer to a thickness of typically 500 to 2000 A.

Finally the replica block 30 which is now metalized, may be mounted to an electroplating fixture and electroplated with gold to a thickness of typically 1 to 3 microns. This thick gold reduces the electrical resistance of the replica block 30 surface and provides a sufficiently thick metal for soldering or wire bonding. After plating the replica block 30 is rinsed with DI water, blown dry with nitrogen and inspected with optical and scanning electron microscopy for defects.

Although the present invention is described in terms of the fabrication of millimeter and sub-millimeter wavelength waveguide components using mastering/casting/molding techniques, it will be appreciated that alternative structures can also be fabricated by the present method, such as oscillators, multipliers, amplifiers, detectors and mixers with active and passive components suspended within the channel structures formed on the wafer.

Obviously, numerous modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.

WHAT IS CLAIMED AS NEW AND DESIRED TO BE SECURED BY LETTERS PATENT OF THE UNITED STATES IS:

1. A method of fabricating a millimeter or submillimeter wavelength component, comprising the steps of:

obtaining a first master millimeter or submillimeter wavelength component;

forming at least one first mold from the first master; and

forming at least one first replica of the millimeter or submillimeter component using the first mold.

2. The method according to Claim 1, wherein the step of obtaining a first master comprises:

providing connector ports, waveguide horns, slots, and interference relief regions into a millimeter or submillimeter wavelength component block; and

rounding the edges of the component block.

3. The method according to Claim 2, wherein the step of obtaining a first master further comprises:

providing a non-integrally formed backshort tuned to a desired wavelength in a channel of the millimeter or submillimeter wavelength component block.

4. The method according to Claim 3, wherein the step of obtaining a first master further comprises:

providing a thin protective and/or release coating layer in active surfaces of the first master.

5. The method according to Claim 4, wherein the step of obtaining a first master further comprises:

providing a taper on an outer edge of the first master.

6. The method according to Claim 5, wherein the step of obtaining a first master further comprises:

providing alignment features on the first master.

7. The method according to Claim 1, wherein the step of forming at least one first mold further comprises:

providing a cylinder which confines a liquid molding resin and provides support for cured, solid molding resin;

providing a baseplate which is attached to the first master; and

pouring the molding resin into a cavity formed by the cylinder surrounding the first master and the baseplate.

8. The method according to Claim 7, wherein the step of forming at least one first mold further comprises:

providing extensions in the mold reinforcing plate that adhere with the molding resin in the cavity.

9. The method according to Claim 8, wherein the step of forming at least one first mold further comprises:

curing the molding resin in the cavity; and

extracting the first master from the cured molding resin.

10. The method according to Claim 1, wherein the step of forming at least one first replica further comprises:

pouring casting resin into the first mold; and

adding a backside former plate or backside insert over the first mold.

11. The method according to Claim 10, wherein the step of forming at least one first

replica further comprises:

providing a threaded extension in the backside former plate over the first mold into the casting resin so as to form a threaded hole in a back side of the first replica;

attaching a threaded element to the threaded hole;

removing the first replica by applying force to the threaded element.

12. The method according to Claim 11, wherein the step of forming at least one first replica further comprises:

curing the first replica; and

metalizing internal surfaces of the first replica.

13. The method according to Claim 1, further comprising:

obtaining a second master which is designed to mate with the first master;

forming at least one second mold of the second master;

forming at least one second replica from the second mold;

metalizing both replicas;

joining the first and second replicas so as to form a complete millimeter or submillimeter wavelength component.

14. The method according to Claim 13, wherein the step of obtaining a second master comprises:

providing connector ports, waveguide horns, slots, and interference relief regions into a millimeter or submillimeter wavelength component block; and

rounding the edges of the component block.

15. The method according to Claim 14, wherein the step of obtaining a second master further comprises:

providing a non-integrally formed backshort tuned to a desired wavelength in a channel of the millimeter or submillimeter wavelength component block.

16. The method according to Claim 15, wherein the step of obtaining a second master further comprises:

providing a thin protective and/or release coating layer in active surfaces of the second master.

17. The method according to Claim 16, wherein the step of obtaining a second master further comprises:

providing a taper on an outer edge of the second master.

18. The method according to Claim 17, wherein the step of obtaining a second master further comprises:

providing alignment features on the second master.

19. The method according to Claim 13, wherein the step of forming at least one second mold further comprises:

providing a cylinder which confines a liquid molding resin and provides support for cured, solid molding resin;

providing a baseplate which is attached to the second master; and

pouring the molding resin into a cavity formed by the cylinder surrounding the second master and the baseplate.

20. The method according to Claim 19, wherein the step of forming at least one second mold further comprises:

providing extensions in the mold reinforcing plate that adhere with the molding resin in the cavity.

21. The method according to Claim 20, wherein the step of forming at least one second mold further comprises:

curing the molding resin in the cavity; and

extracting the second master from the cured molding resin.

22. The method according to Claim 13, wherein the step of forming at least one second replica further comprises:

pouring casting resin into the second mold; and

adding a backside former plate or backside insert over the second mold.

23. The method according to Claim 22, wherein the step of forming at least one second replica further comprises:

providing a threaded extension in the backside former plate over the second mold into the casting resin so as to form a threaded hole in a back side of the second replica;

attaching a threaded element to the threaded hole;

removing the second replica by applying force to the threaded element.

24. The method according to Claim 23, wherein the step of forming at least one second replica further comprises:

curing the second replica; and

metalizing internal surfaces of the second replica.

25. The method according to Claim 2, wherein the step of obtaining a first master further comprises:

providing an integrally formed backshort tuned to a desired wavelength in a channel of the millimeter or submillimeter wavelength component block.

26. The method according to Claim 15, wherein the step of obtaining a second master

further comprises:

providing an integrally formed backshort tuned to a desired wavelength in a channel of the millimeter or submillimeter wavelength component block.

27. The method according to Claim 7, wherein the cylinder which confines the liquid molding resin has an expansion coefficient equal to an expansion coefficient of the molding resin.

28. The method according to Claim 19, wherein the cylinder which confines the liquid molding resin has an expansion coefficient equal to an expansion coefficient of the molding resin.

29. The method according to Claim 3 or 25, wherein the backshort is made of a material different from the first master.

30. The method according to Claim 15 or 26, wherein the backshort is made of a material different from the second master.

31. The method according to Claim 7, wherein the step of forming at least one first mold further comprises adding a mold reinforcing plate over the cavity.

32. The method according to Claim 19, wherein the step of forming at least one second mold further comprises adding a mold reinforcing plate over the cavity.

33. The method according to Claim 10, wherein the backside insert is made of a transparent or opaque material.

34. The method according to Claim 22, wherein the backside insert is made of a transparent or opaque material.

35. The method according to Claim 33, wherein the casting resin is cured through the backside insert made of the transparent or opaque material.

36. The method according to Claim 34, wherein the casting resin is cured through the backside insert made of the transparent or opaque material.

37. A millimeter or submillimeter wavelength device fabricated according to process of anyone of Claims 1-36.

ABSTRACT OF THE DISCLOSURE

A method of reproducing a millimeter or submillimeter wavelength device including forming a master of the millimeter or submillimeter wavelength device, forming at least one mold from the master, and forming at least one replica of the millimeter or submillimeter device using the mold. The master is made by forming connector ports, channels and grooves into a block of solid material, providing a backshort in the appropriate locations, and providing a thin protective coating layer if necessary. The master is optimized for the production of precision waveguide structures with unique features such as rounded edges, tapered sidewalls and the absence of features which would inhibit the easy release of the master or the cast replica. The mold is formed by providing a cavity with a baseplate which is attached to the master, pouring a mold resin into the cavity surrounding the master. The mold is cured and the master is extracted from the cured mold resin. The replica is formed by pouring a casting resin into the mold, curing the resin and removing the replica from the mold. A metalization layer is then added to internal surfaces of the replica and two mirror image replicas are joined so as to form a complete a millimeter or submillimeter device.

Mastering, Molding and Casting (MMC) Technology For High Precision Fabrication Of Millimeter And Submillimeter Wavelength Hollow Waveguides, Channels, Horns And Assemblies

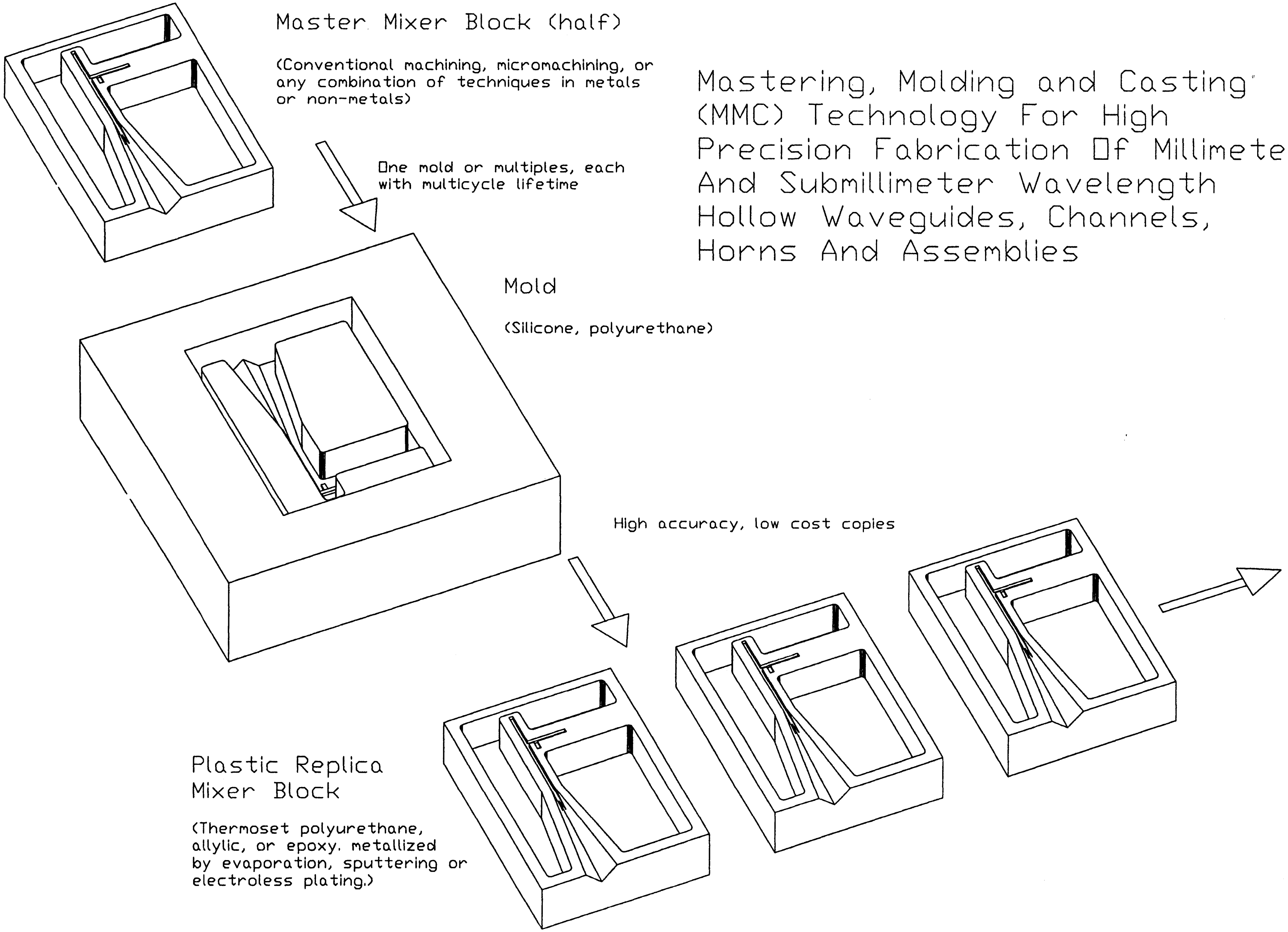


Fig. 2A Machined Mixer Block
For Direct Use

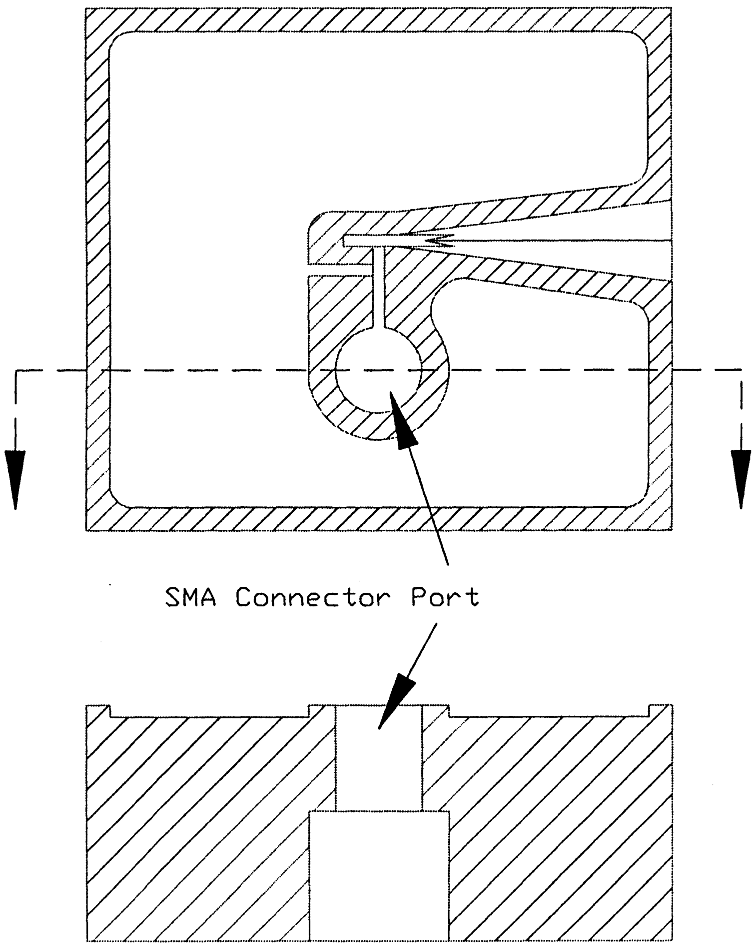


Fig. 2B Machined Mixer Block
Molding/Casting Master

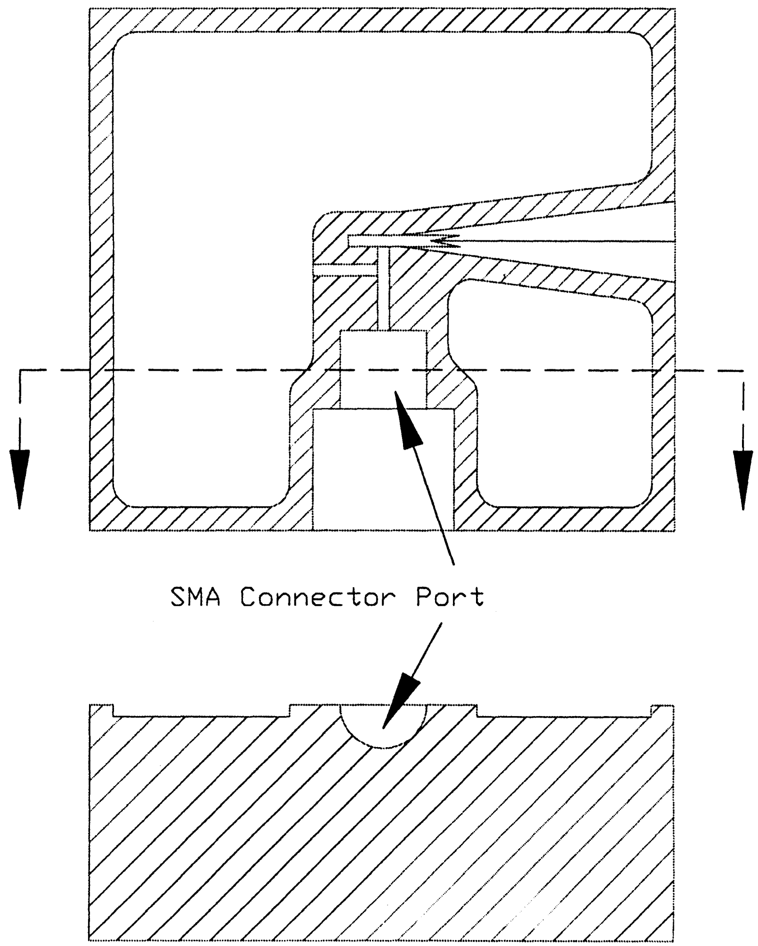


Fig. 2C Machined Mixer Block
Molding/Casting Master:
With Rounded Vertical Edges

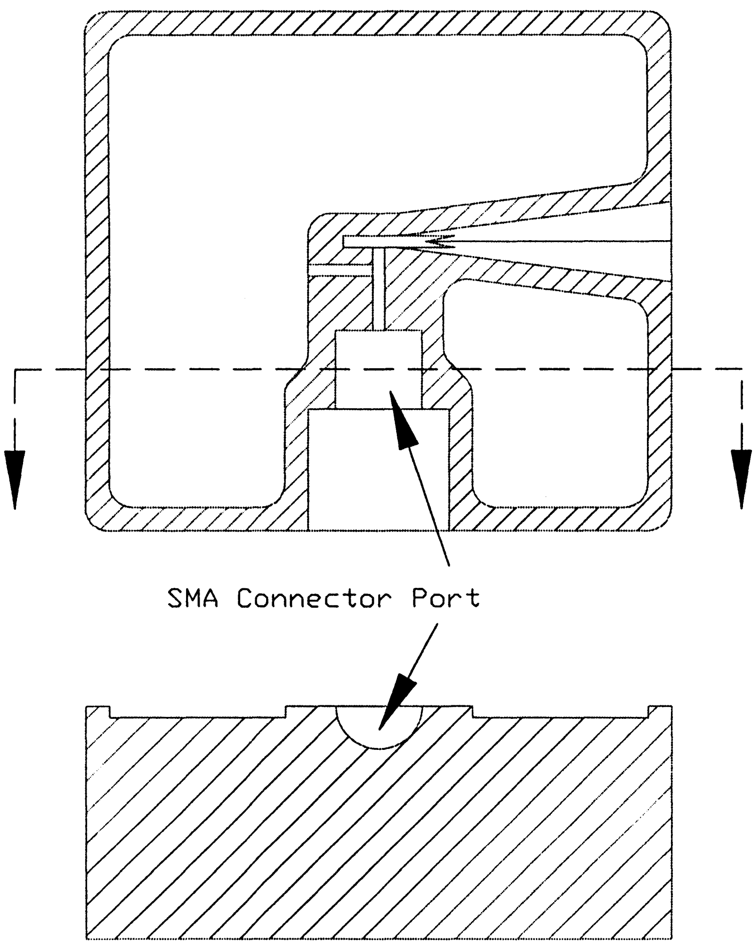


Fig. 2D Machined Mixer Block
Molding/Casting Master:
With Rounded Vertical Edges
And Sidewall Taper

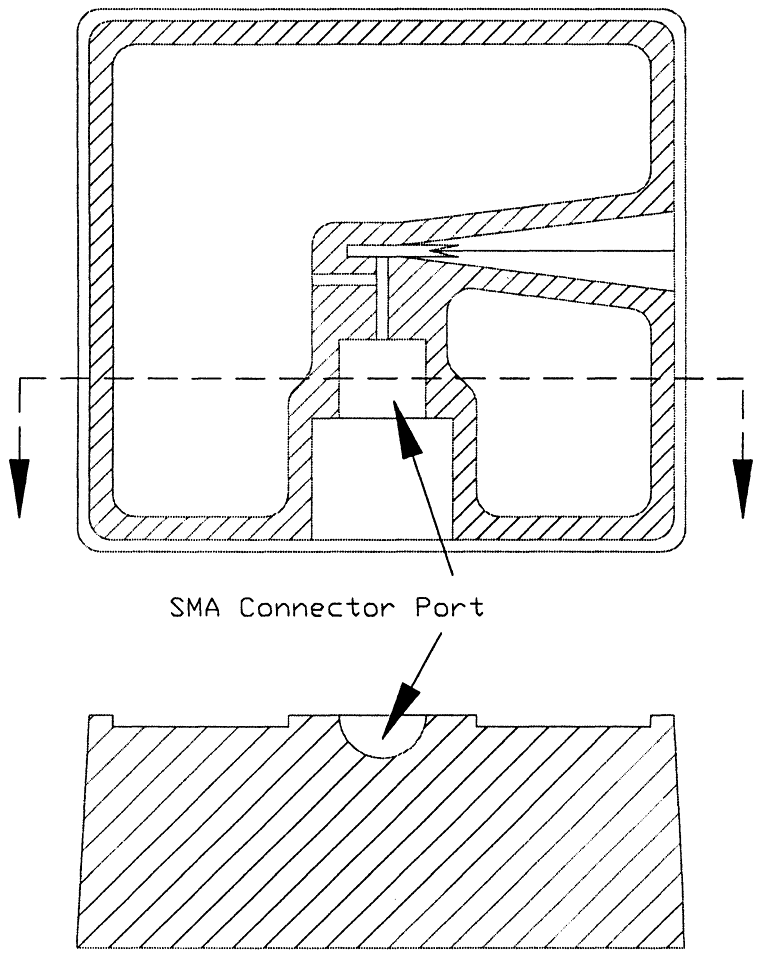


Fig. 3a Machined Mixer Block Molding/Casting Master: As Machined With No Backshort

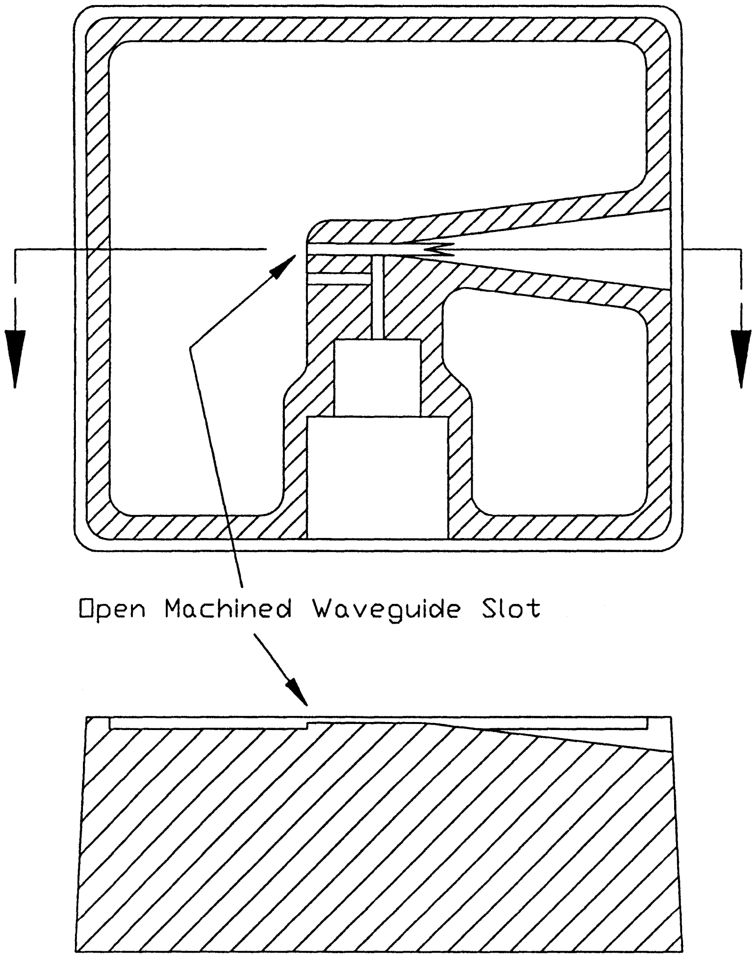


Fig. 3b Machined Mixer Block Molding/Casting Master: With Backshort Added

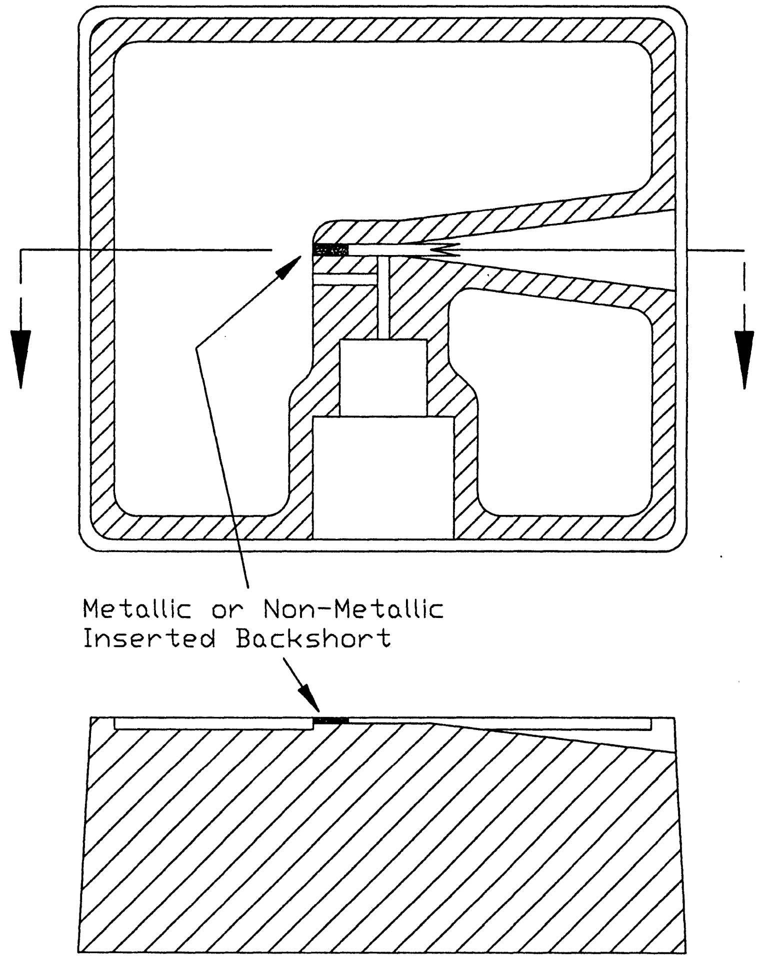


Fig. 3c MMC Technology Mold With Monolithic Integrated Backshort

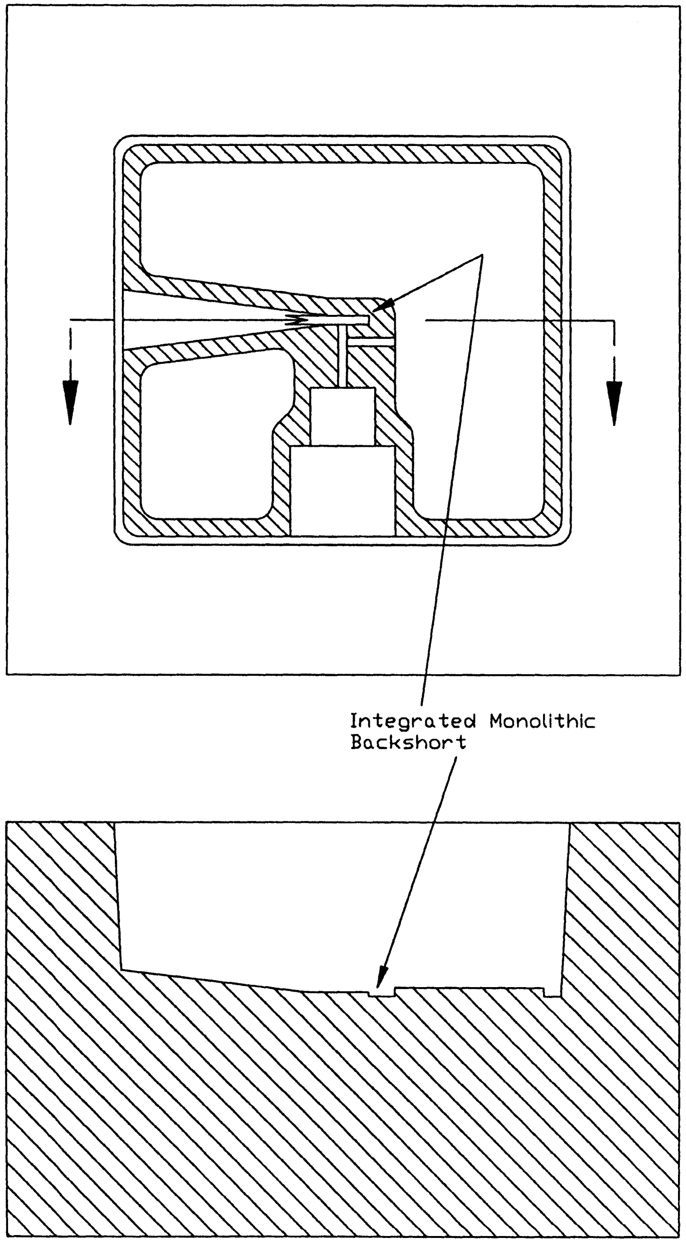


Fig. 3d MMC Technology Plastic Replica Mixer Block With Monolithic Integrated Backshort

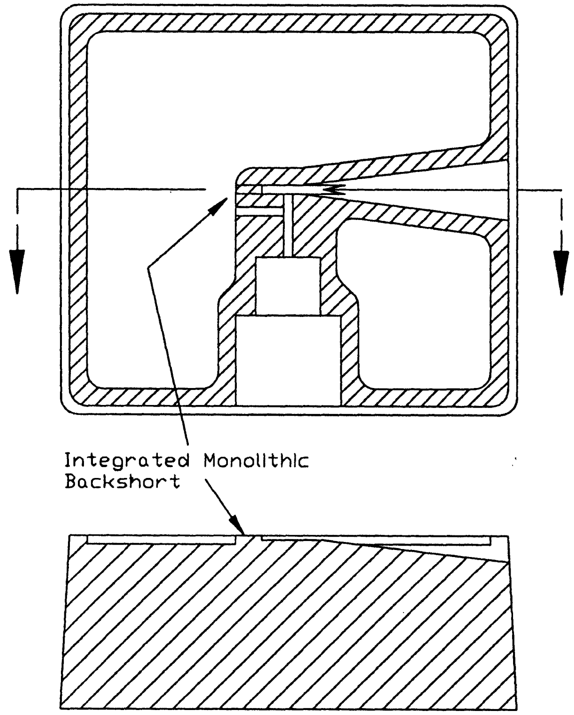


Fig. 4a Composite Master Mixer Block Fabrication

machinable material milled to size and ground flat

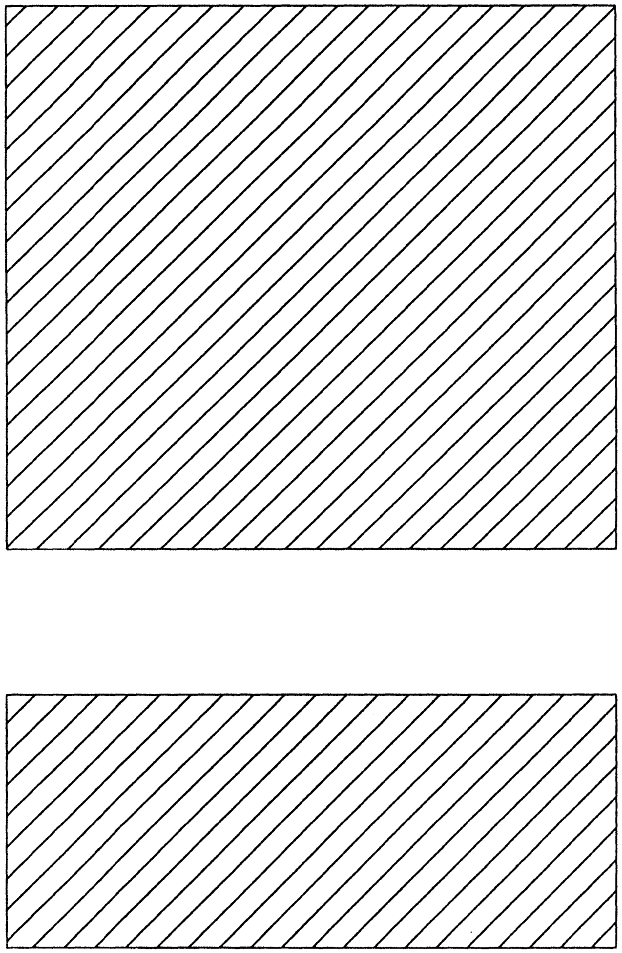


Fig. 4b Composite Master Mixer Block Fabrication

recess areas milled or etched away leaving regions for horn and connector

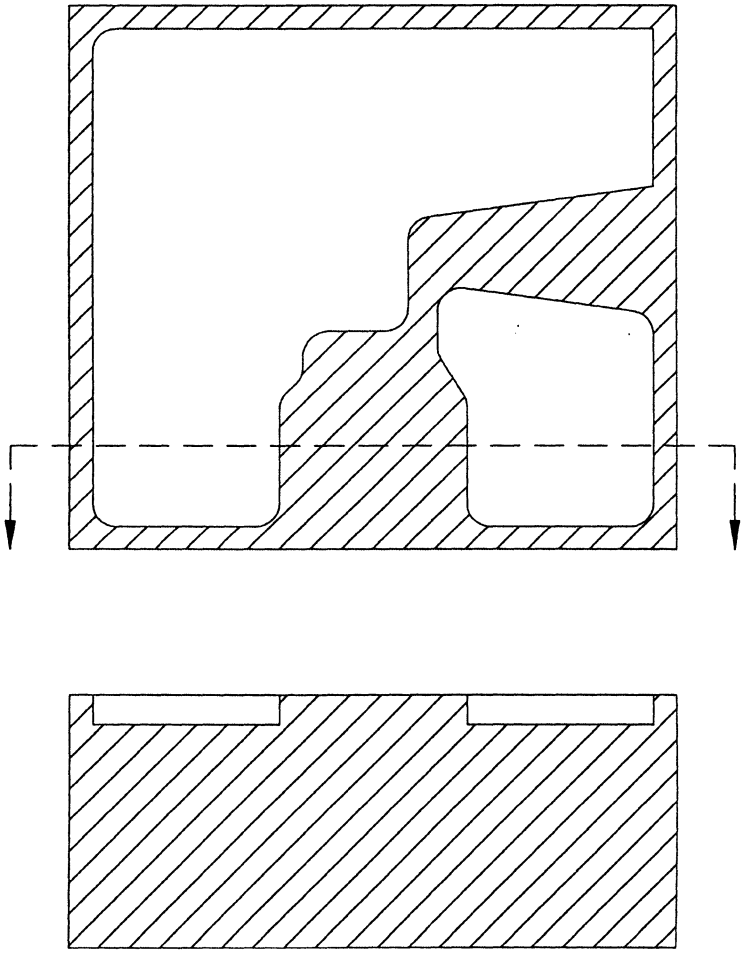


Fig. 4c Composite Master
Mixer Block Fabrication

SMA connector port milled

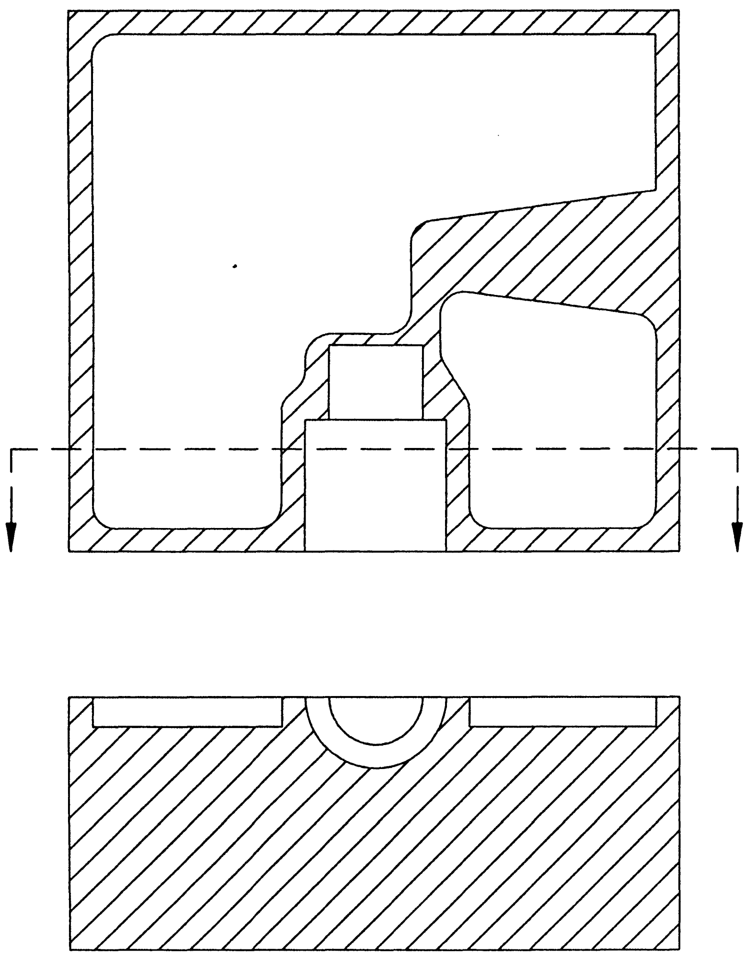


Fig. 4d Composite Master
Mixer Block Fabrication

diagonal horn milled

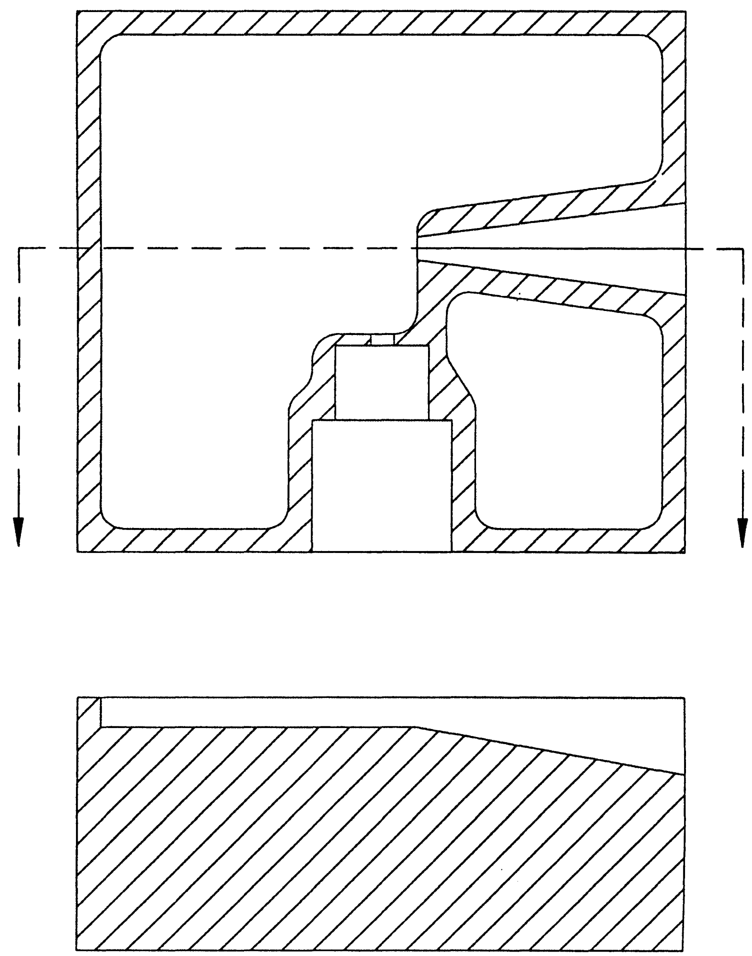


Fig. 4e Composite Master
Mixer Block Fabrication

surface features filled in
with photopolymer (e.g., SU-8)

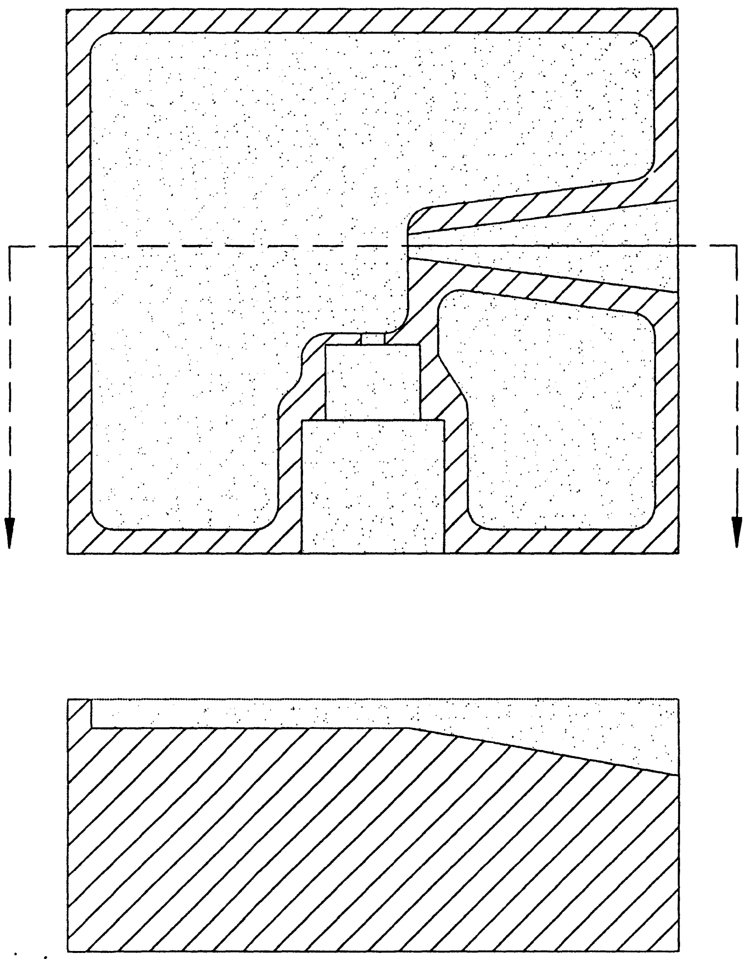


Fig. 4f Composite Master
Mixer Block Fabrication

waveguide channels patterned
in photopolymer

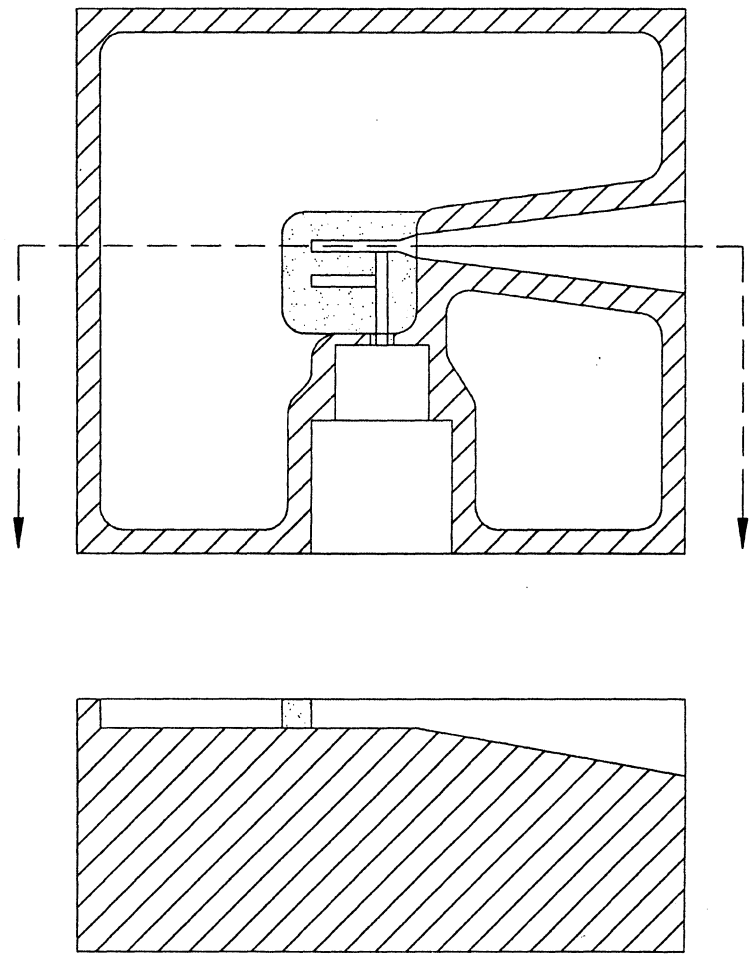
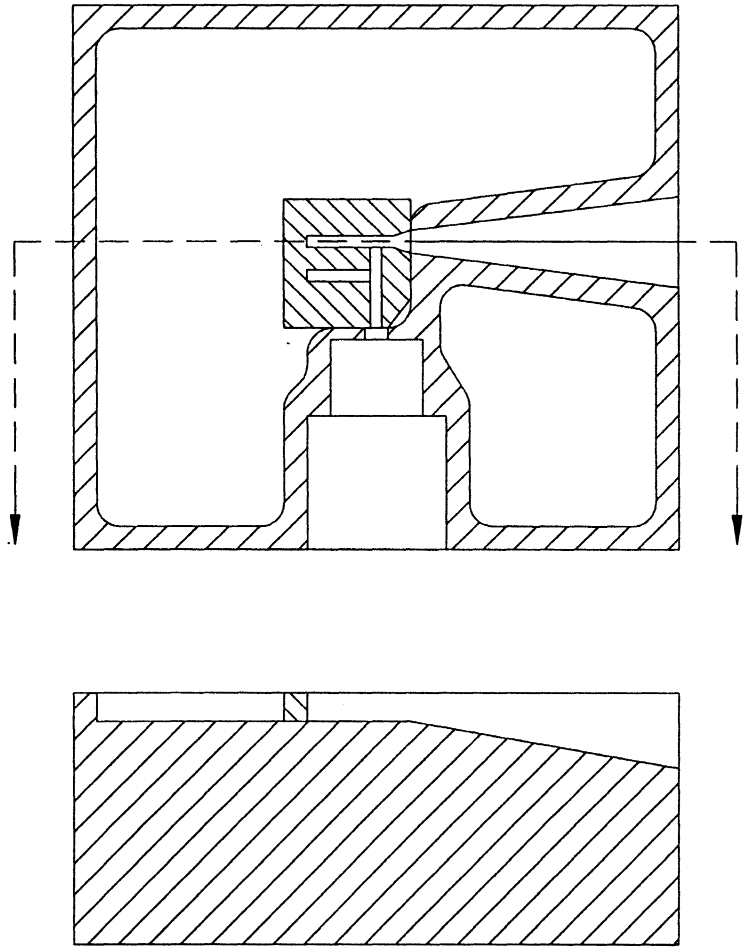


Fig. 4g Composite Master Mixer Block Fabrication

channel circuit aligned and bonded in place



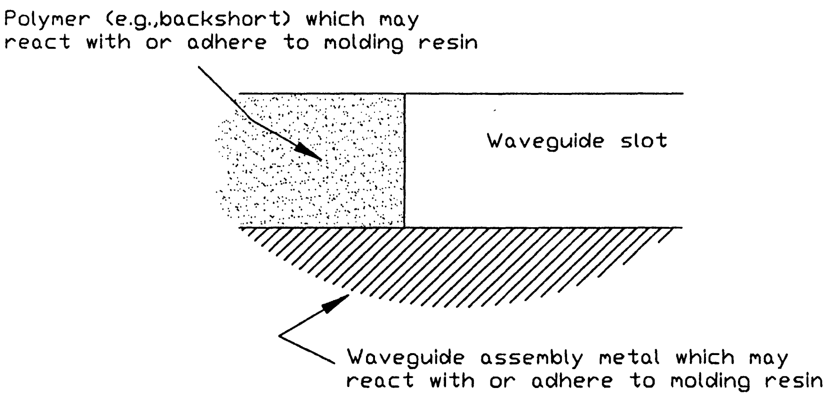


Fig. 5a Cross Section Of Composite Master Illustrating Materials Vulnerable To Attack By Or Adhesion To Molding Resin

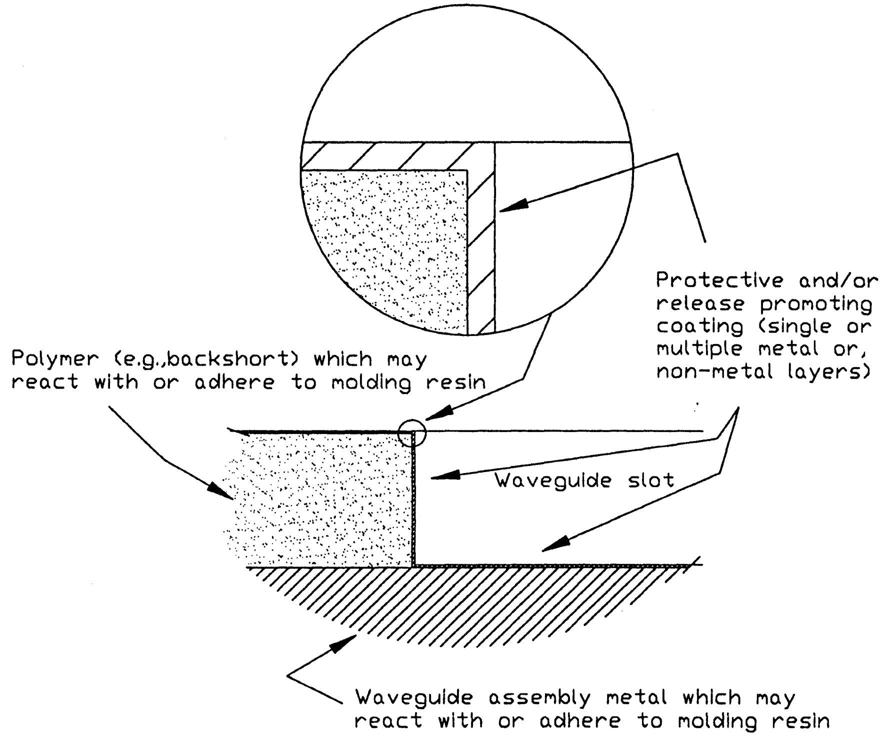
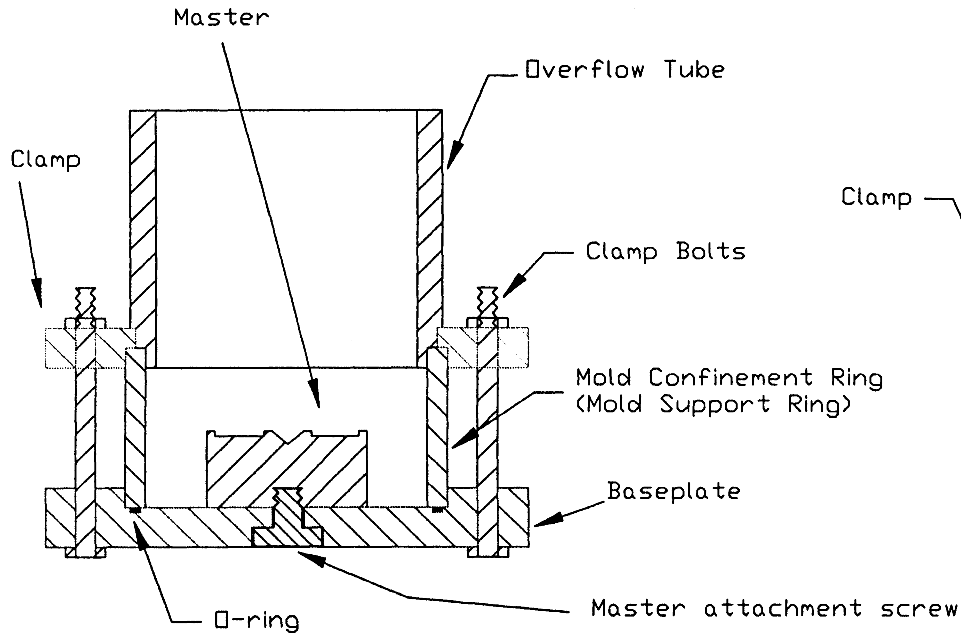
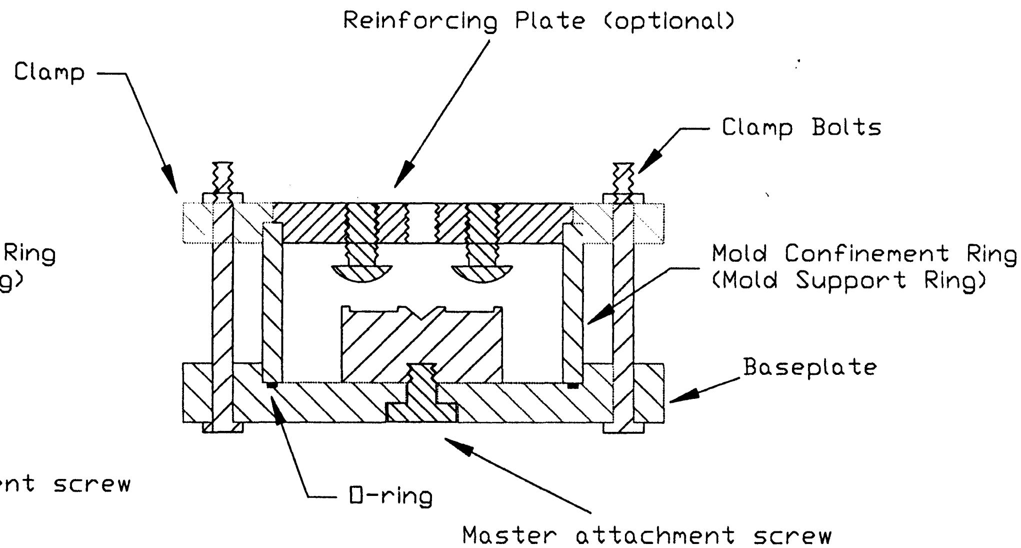


Fig. 5b Cross Section Of Composite Master Illustrating Materials Vulnerable To Attack By Or Adhesion To Molding Resin Which Are Protected By A Thin Film Coating

Figure 6. Molding Fixture Assembly



6A. Molding Fixture Assemby
With Overflow Tube



6B. Molding Fixture Assembly
With Reinforcing Plate

Figure 7. Backside Options:
Backside Former Plate and Backside Insert

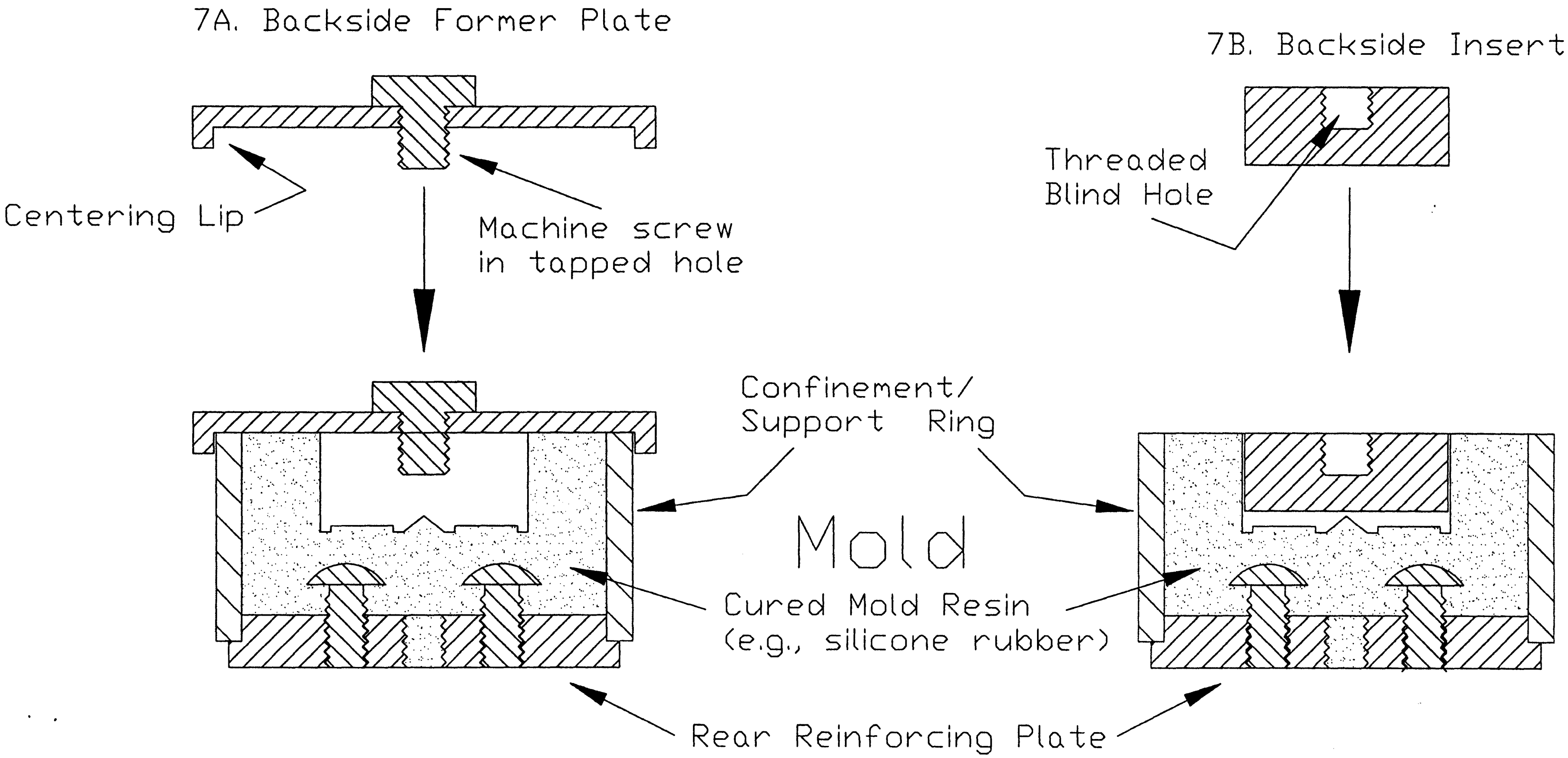
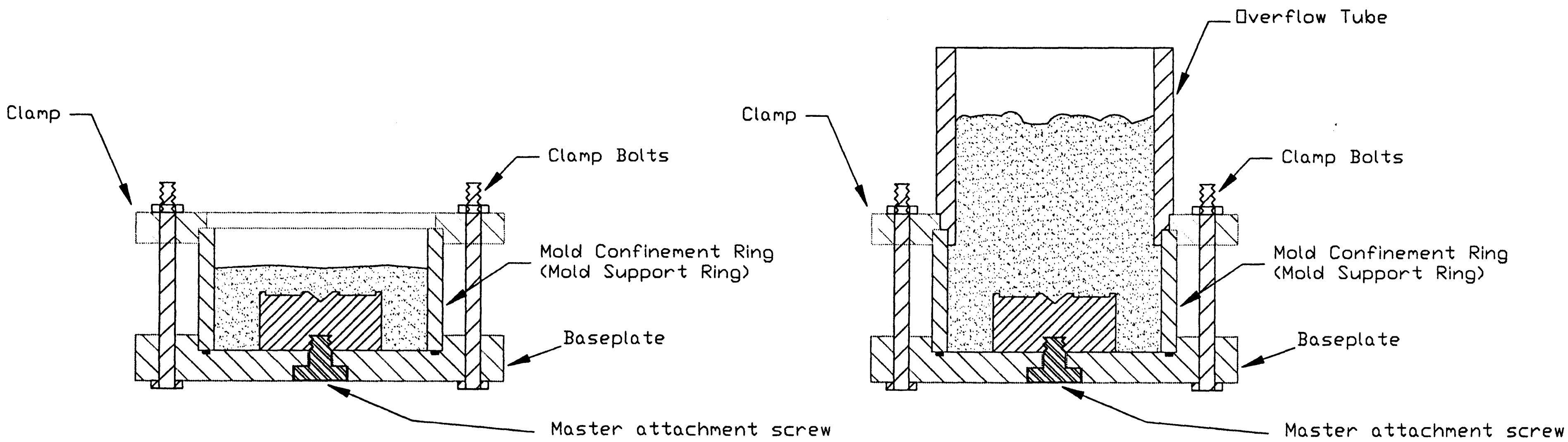


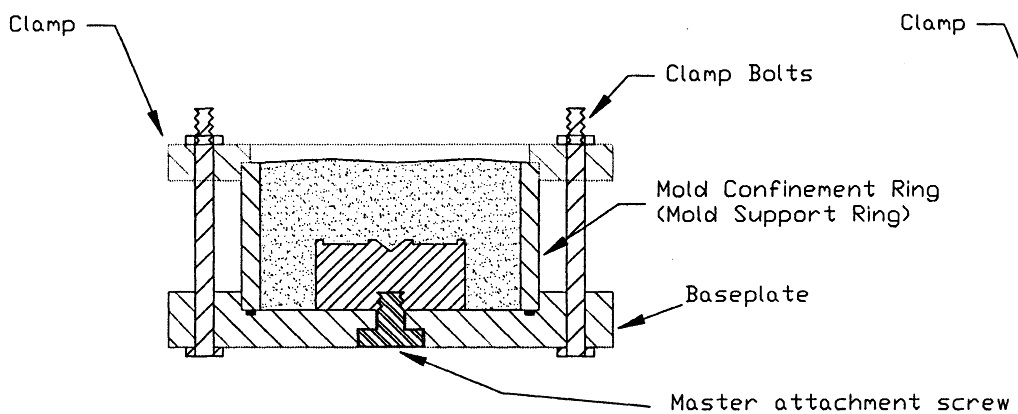
Figure 8. Mold Fabrication Process



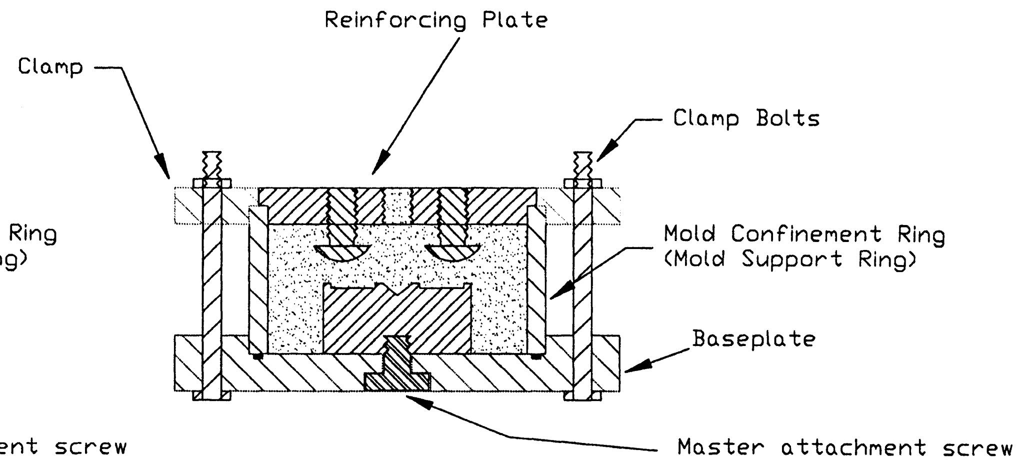
8A. Pour Resin Into Mold

8B. Vacuum Degas

Figure 8. Mold Fabrication Process

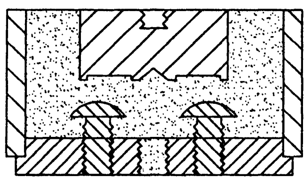


8C. Fill Mold With Resin

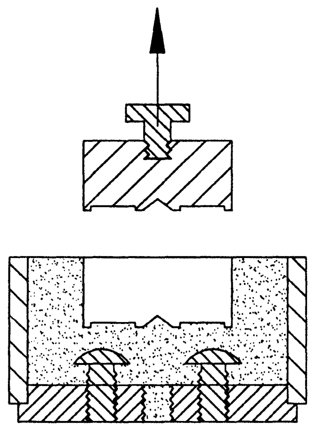


8D. Insert Reinforcing Plate And Cure

Figure 8. Mold Fabrication Process

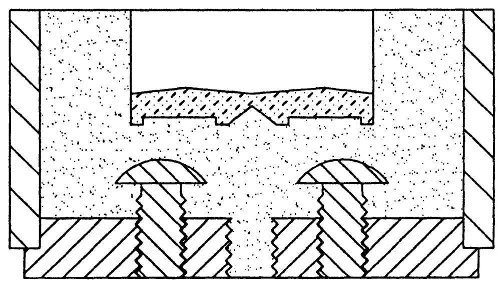


8E. Remove Mold With Master From Clamp

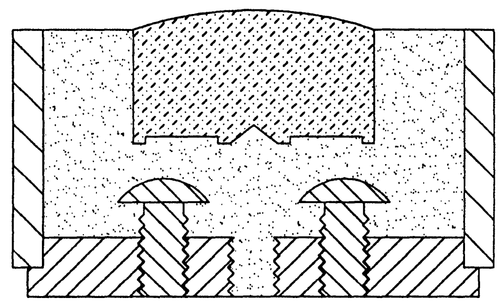


8F. Demold Master

Figure 9. Casting Process

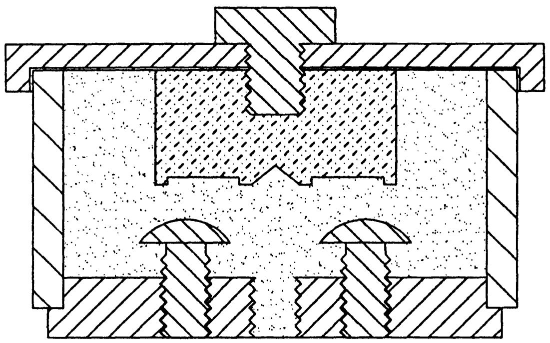


9A. Pour PUR Resin Into Mold Cavity And Remove Air Bubbles

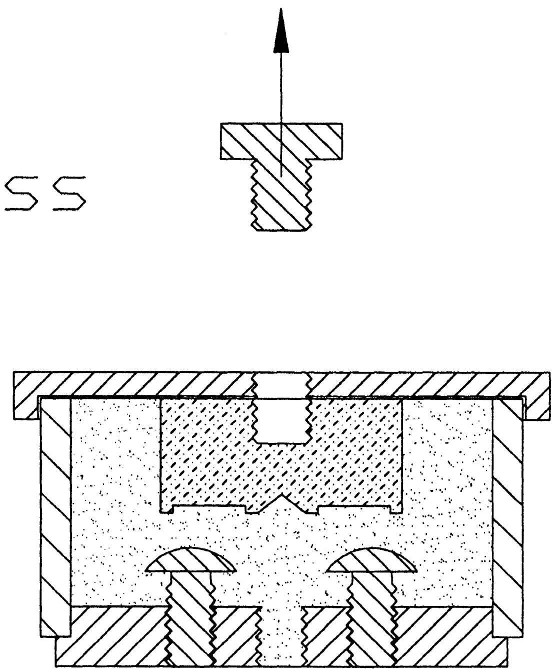


9B. Fill Mold Cavity With PUR Resin

Figure 9. Casting Process

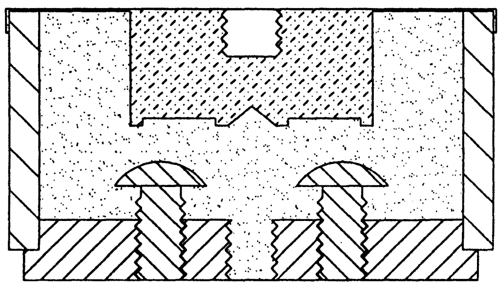


9C. Install Backside Former And Cure

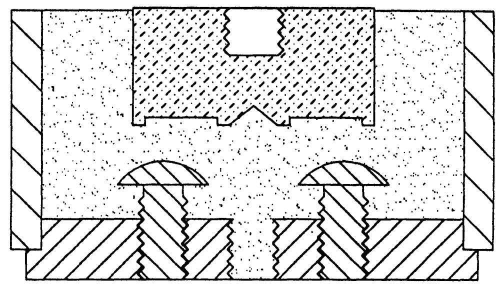


9D. Remove Backside Former Screw

Figure 9. Casting Process

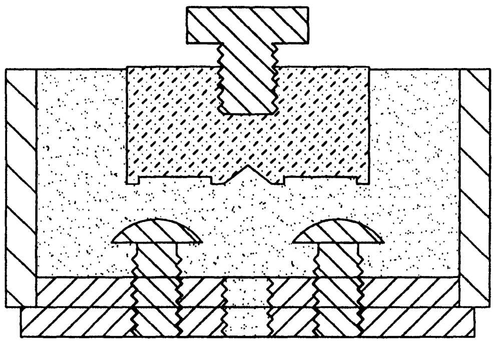


9E. Remove Backside Former

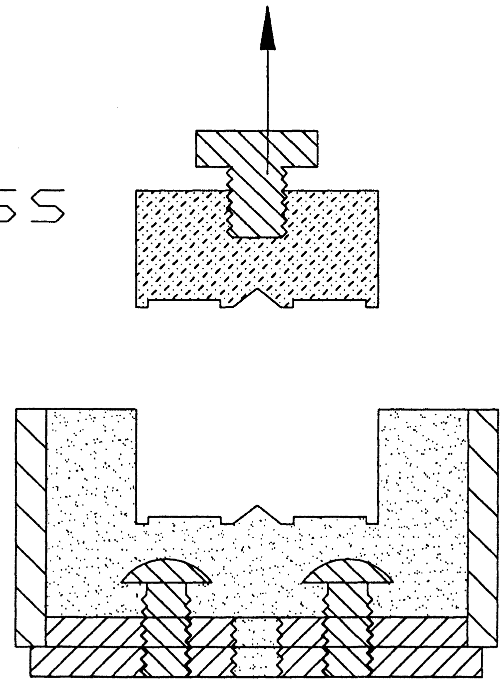


9F. Remove Excess PUR From Mold

Figure 9. Casting Process



9G. Thread Screw Into Formed Threads



9H. Remove Casting From Mold

8-17-98

NATIONAL RADIO ASTRONOMY OBSERVATORY
2015 IVY ROAD, SUITE 219 CHARLOTTESVILLE, VIRGINIA 22903-1733
TELEPHONE 804-296-0211 FAX 804-296-0324

Attachment B

Royalty-free License Agreement between

University of Virginia Patent Foundation

National Radio Astronomy Observatory

Description of the Millimeter Array project

September 18, 1998

Millimeter Array

Public Information

General Information

Partners

MMA Development

MMA Science

Project Book

Vendor Information

News & Events

Memo Series

Library

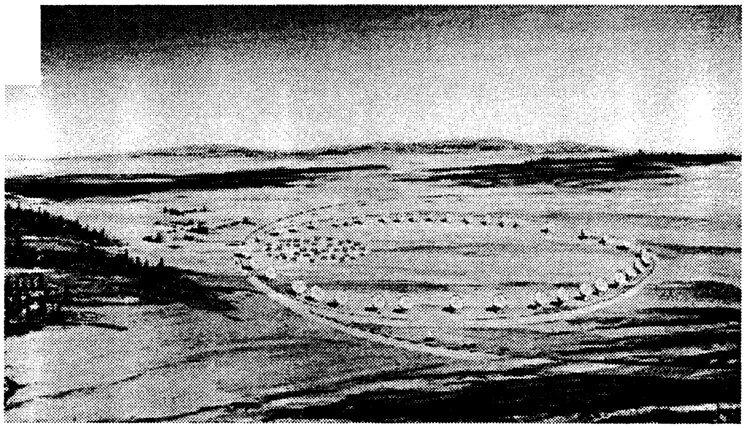
The Millimeter Array (MMA) Project has begun the Design and Development phase of building a millimeter wavelength interferometer. The project, funded by the National Science Foundation, includes thirty-six 10-meter antennas arranged in large circular patterns between 80 m and 3 km across. The array will be located atop a 16,400 foot Chilean plateau. This telescope will be the largest and most sensitive instrument in the world at millimeter and submillimeter wavelengths.

Last update 2 September 1998
Send questions or comments to:
kweather@nrao.edu

General Information

What is the MMA? | Travel Information | Safety Guidelines

What is the Millimeter Array?



MMA antennas arranged in the 200 meter ring-like "C" array.

The Millimeter Array (MMA) is a millimeter wavelength telescope funded by the National Science Foundation. The MMA design has come a long way and includes:

- Thirty-six 10-meter antennas on a very high mountain top site
- Imaging instrument in all atmospheric windows between 10 mm and 350 microns
- Array configurations from approximately 80 meters to 10 km
- Spatial resolution of 10 milliarcseconds, 10 times better than the VLA and the Hubble Space Telescope
- Able to image sources arcminutes to degrees across at one arcsecond resolution
- Velocity resolution under 1 km/sec
- Faster and more flexible imaging instrument than the VLA
- Largest and most sensitive instrument in the world at millimeter and submillimeter wavelengths
- Point source detection sensitivity 20 times better than the VLA

MMA Home | Development | Science | Partners | Memos | Library | News & Events

MMA Project Book, Chapter 1.

Robert Brown
Last modified July 8 1998

MMA PROJECT BOOK: INTRODUCTION

Design of the Millimeter Array (MMA) is an ambitious undertaking. Uniquely, it is designed as a complete imaging instrument with the capability to image astronomical objects on angular scales from milliarcseconds to many degrees. It will measure fluctuations in the microwave background that are isotropically distributed all over the sky and it will image the kinematics of streams of gas smaller than 500 parsecs in length that are flowing onto the massive blackholes of quasars 3000 Megaparsecs away from us. MMA imaging on this tremendous range in angular scales, from degrees to less than 50 micro-arcseconds, brings with it both enormous capabilities for astrophysical research and enormous challenges for the technical design of the instrument. It is the purpose of the MMA Project Book to provide a comprehensive account of the scientific requirements of the MMA and the approaches being taken in design, fabrication and integration of the instrument to reach those goals.

The Millimeter Array will be constructed in two stages: a 3-year Design and Development (D&D) phase will be followed by six years of construction. The Design and Development effort has as its goal completion of designs for the array instrumentation including prototypes of the highest risk instruments or modules and decisions made among competing designs where that is necessary. The D&D work has a specified task, staff, timescale and budget. The D&D effort is very well defined. In contrast, the construction planning for the MMA involves open questions, answers for which are among the products or deliverables of the D&D work. The operations model for the MMA is even less well developed because it hinges not only on a clear understanding of what must be operated and maintained--the product of the D&D work--but also on a realistic assessment of what operational aspects of the MMA can and cannot be done in the vicinity of the MMA site, elsewhere in Chile, or which must be done at a U.S. base. The answers to these questions will become clear as experience is gained in Chile. Nevertheless, this MMA Project Book includes a description of the planning for the entire project, D&D, construction and operations. Where there are outstanding issues or several options still available these topics are included in the Project Book and noted as to be determined. The MMA Project Book is meant to be a living document growing both in breadth so as to encompass the entire project and in depth as design, construction and operations decisions are made.

For each task the MMA Project Book summarizes requirements and the technical approach being taken to meet those requirements. Where one task interacts with another either in design or integration, the interface requirements are specified and the integration assumptions being made are noted--or noted as missing and in need of definition.

The Project Book is meant to be the fundamental reference manual for what is and is not planned in the project. It is written by those people working in the project and its principal readership is meant to be other people in the project. As decisions are made or options are adopted the Project Book will evolve; that will be done using an audit trail of additions and changes appended to each chapter. The Project Book is of value only if it is kept up-to-date. For this reason the Project Book will be kept on line: the version that is printed from the web will always be the latest version.

MMA Project Book, Chapter 2

MMA SCIENCE REQUIREMENTS

Frazer Owen,
Last revised July 8 1998

Introduction

The concept of the MMA was first discussed in 1981 and written about in 1982 (MMA memo 1). From this beginning the ideas have evolved through numerous advisory committees and large scientific workshops. The goal has always been to produce a cutting edge instrument which will make great contributions in almost all areas of astrophysical research. As with the VLA, there are topics which now appear to be the most important and interesting areas for major progress with the array. These include cosmology, galaxy, star and planet formation, and chemistry/creation of the building blocks of life. However, with the VLA, other areas of astrophysics than the ones the instrument was sold on, have turned out to dominate the research; the same may be expected of the MMA. Thus the scientific requirements of the MMA have always been to build a very versatile instrument which, like the VLA, will be an important tool for decades to come regardless of the direction research takes us.

The most recent summary of the science goals of the US community are summarized in five reports from the November 1995 Tucson Science Workshop. These are divided into

1. Cosmology and Extragalactic
2. Star Formation and Stellar Evolution
3. Galactic Molecular Clouds and Astrochemistry
4. Solar System
5. Sun and Stellar

While these different areas emphasize different capabilities, they all require imaging over a range of resolutions and frequencies. This means that we must build an instrument which can image objects from milliarcsec (microarcsec for VLBI) to scales at least of 10's of minutes. This implies that an important feature of the array is that it must be reconfigurable in size , like the VLA, to match the problem and that it must be able to image objects larger than the antenna primary beam. Since the scales of many of the most interesting objects are much larger than the primary beam (which decreases in size linearly with wavelength), much of the observing may not use the interferometer mode at all but may use the array as a large collection of single dishes. This implies that sensitive, stable total power mode is an important requirement. However, current wisdom is that the interferometer mode will come closer to the theoretical sensitivity than will be possible for total power. Thus it appears to be attractive to do as many experiments as possible in interferometer mode. This, in turn, argues for smaller antennas. However, the desire for as simple an instrument as possible and as large a collecting area as possible for sensitive work on small sources conflicts with this desire at some level which leaves us a goal of obtaining the best compromise solution for a given amoount of money. This is the primary design conflict for the array.

In section II, I summarize the general instrumental requirements based on the science requirements as detailed in the five science reports listed above. In section III, I will outline some of the implications for the array to be able to reach these goals.

General Requirements

1. Frequency Coverage

The instrument needs to cover all the available frequency windows between about 30 and 900 GHz. These requirements are summarized in the MMA Frequency Bands whitepaper . This requires an outstanding site as discussed in the Site Selection Document.

2. Spectral Line and Continuum

   The MMA must operate as both a sensitive spectral line and continuum array. This implies using the widest continuum practical from the point of view of the IF and the correlator which appears now to be 8 GHz and a flexible correlator as described in the MMA Correlator Whitepaper .
3. Sensitivity

   The array must maximize both point source and surface brightness sensitivity. For antennas with the same overall properties, this requires maximizing the different quantities, nD^2 (for point source sensitivity), nD (for surface brightness sensitivity in a sparsely filled array) and $n^{(1/2)}$ (for a tightly packed array or total power mode). See MMA Memo #177.
4. High Resolution

   Given the expected brightness and size of sources considered in the science documents, this implies baselines of at least 3km and 10km as a design goal. This requirement demands the MMA be adequately phase stable both internally and in the presence of atmospheric phase flucuations. This will be discussed further in section 3.
5. Large Source Imaging

   On the other end of the size scale, this implies imaging objects both close to and bigger than the primary beam. This requirement has several implications. First, 3)+ 4) + 5) require that the array be reconfigurable into configurations optimized for the resolution and sensitivity required by each experiment. Second, the array must be able to make large mosaicked images (multiple pointings) to image regions on the order or larger than the primary beam. Third, the array must have a sensitive, stable total power system so that spatial frequencies smaller than are available in interferometer mode can be measured. Since the primary beams at the highest frequencies for antennas on the order of 10m are < 10 arcsec, modes 2 and 3 should be very common, perhaps the vast majority of all observations with the array.
6. High Fidelity Imaging

   Especially in the modes discussed in 5), a significant fraction of the experiments and some the most important require high fidelity imaging. That is the signal-to-noise is high enough and source complex enough that errors in pointing and calibration can degrade the scientific usefulness of the experiment (Cornwell memo/Rupen memo). Such problems require 1) excellent pointing, 2) high quality amplitude and 3) phase calibration which will be discussed in section 3.
7. Polarization

   Both linear and circular polarization of lines and continuum emission is a significant part of the MMA science program. At centimeter and longer wavelengths interferometers produce linear polarization by correlating the opposite circular polarizations from different antennas, that is R with L and L with R. However, it appears technically difficult to do this at millimeter wavelengths across the broad bands we want with the MMA. Thus it seems best to observe in the more natural linear polarization with the MMA. This means we crosscorrelate to calculate the V stokes parameter; we get I, Q and U from linear combinations of the two linear correlations. This requires both linears be present all the time and that either their relative gains remain very stable and/or we have the necessary internal calibration signals to measure their changes. (see Cotton, 1998).

8. Solar observations

   Requirements for observing the sun are discussed in the Sun and Stars science document and by Bastian et al, 1998.
9. VLBI

   The highest resolution with the MMA will be obtained from VLBI observations using the MMA as a single element. The requirements for this are discussed by Claussen and Ulvestad, 1998.
10. Pulsar/high speed

    Pulsar observations will require a gating mode with the correlator as well as a sum port like the VLA which can be attached to specialized external recording equipment. This latter capability would also be available for any high speed phenomena which may be discovered in the future.

Implications

Several capabilities are implied by these requirements.

1. Phase Stability

   As the frequency increases, the electrical path length through the atmosphere and the electronics must be more and more stable to produce high quality images.
   a. Internal phase stability

      The electronic systems must be stable enough so they they do not degrade the imaging relative to residual atmospheric path length fluctuations. This implies phase stability < 10 degrees at 900 GHz. This needs to be accomplished either by building a very phase stable system or by providing adequate internal calibration signals to calibrate out any remaining path length changes. If some or all of the MMA's frequencies operate in linear polarization, then the relative phase stability between the two receivers at each polarization needs to be high. A reasonable goal is 0.1% stability in the instrumental linearly polarized term. This requires about 0.1 degree stability between the two receivers.
   b. Atmospheric phase stability

      Atmospheric path length changes will be measured and corrected primarily using one of two techniques: fast switching or radiometric correction. In some special cases there may be other modes of phase calibration as well.
      i. Fast Switching

         In this mode the antennas are rapidly cycled between a nearby calibrator and the program source before the atmosphere can change significantly. This mode seems most certain to work but will trade calibration time for integration time on the source and thus reduces the effective instrumental sensitivity. It requires that the antennas be able to change pointing position very rapidly and stop quickly. Since most of the bright sources are available at 90 GHz or lower frequencies, it also requires that the array be capable of changing frequency bands during the slew between sources and that the internal phase differences between the observing and calibration bands be stable. See MMA Memo #139.
      ii. Radiometric Phase Correction

         Since water vapor in the atmosphere produces both opacity and changes in electrical path length, measurements of the sky brightness at millimeter wavelengths can be combined with model atmospheres and/or local calibration to estimate the phase changes caused by the atmosphere. However, these measurements require very stable total power radiometry. This technique sohould have much less observing overhead associated with it than the fast switching technique. However, it may be limited by the instrumental stability and the calibration/atmospheric modelling we are able to achieve. These problems are discussed in Carilli et al, 1998.

iii. Other techniques

In some cases there will be sources in the same primary beam which can be used as phase calibrators, either at the same frequency or at some different frequency than the observations. In the case where the frequency is different, for example in the case of a maser, the system must be cabable either of simultaneous observations at both frequencies or if different receivers are required of changing bands back and forth in a few seconds.

2. Amplitude stability
   a. Atmospheric

   Atmospheric opacity corrections need to be made often enough to prevent these errors from limiting each experiment. For a detection experiment or under good conditions, this may only require occasional opacity measurements for the entire array. For time variability or under marginal conditions, a more aggressive approach is probably necessary. Thus some form of total power monitoring off-source to allow such corrections to be made on an antennas-based approach is necessary.

   b. Internal
      i. Interferometer mode

      Either the internal stability of the instrument needs to be good enough so that gain changes never limit an experiment or an internal amplitude calibration system (possibly a coherent signal) needs to be available to measure such gain changes.

      ii. Total Power Mode

      Perhaps the most demanding observations which will be made with the MMA will be the total power observations. For sources larger than the primary beam at any frequency the array will depend on this mode for its imaging information. The fluctuations in sky brightness and the instabilities in the receivers and other parts of the system will provide a great challenge to the instrument. The sky fluctuations will need to be dealt with by rapid on-the-fly mapping, that is scanning the antennas over the region of interest fast enough that the sky brightness has not had time to change very much or by rapid beam-switching. Either all the components of the array will need to be extremely stable or some sort of internal calibration will be necessary.

3. Integration times

The fastest integration times may be driven as much by total power and fast mosaicking as by high time resolution. See MMA Memo #192.

4. Contingency Scheduling

At millimeter and submillimeter wavelengths, the atmospheric conditions limit most experiments. That is why we are going to such as an extreme site as Llano de Chajnantor. To make optimum use of the site, we need to schedule experiments when atmospheric conditions allow. Experiments may be limited by atmospheric transparency, phase stability, wind, and possibly other conditions. To match the science to the changing conditions, we will need to schedule the array in real time, rather than blocking out time periods as is traditional on NRAO instruments now.

5. Dataflow

   For such a complex instrument, the astronomer will need a complex, yet friendly, computer system to help the user to deal with the extremely, flexible MMA.

   i. Since the array will be contingency scheduled, the process by which the astronomer submits and schedules a proposal will be different. This may only mean that somewhat flexible schedules, perhaps with more total time scheduled than the experiment will use, are submitted. It could also mean that the observatory computers and/or staff actually prepare the schedule. Also the telescope time allocation process will need to deal with assigning or approving the allowable weather conditions under which the experiment will be carried out.
   ii. Experiments will probably more often be split up to allow them to be scheduled as close to transit as possible to minimize the air mass and opacity. Thus the astronomer will be able to get useful feedback on how an experiment is going during the time it is on the telescope. This needs to include diagnsotics and logs, as well as images. In some cases, these images might be the final output of the experiment. In other cases, the imaging may be too complex for quick turnaround without the astronomer's interaction. In these cases, the images may serve as quality control to allow the astronomer to adjust the parameters of the observation.

       This implies a more sophisticated communications/software system than has been use in astronomy to date.
   iii. Almost real-time feedback to the staff on-site is also necessary to allow them to evaluate if an experiment has been successful. Weather and other data on the site as well as analysis of the quality of the data need to be part of this feedback to allow the scheduler (whether human, machine or some combination) to decide what to do next.
   iv. A final data product which would be a combination of images and uv data also needs to be defined.
   v. Off-line software is needed to allow the astronomer to take advantage of the necessariliy complicated imaging algorithms (often using large mosaics and combining interferometer and total power observations) as well as inspection and analysis of the results.
