Research report 56

DFM(A)- ASPECTS FOR A MICROWAVE WAVEGUIDE RING RESONATOR DESIGN

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ABSTRACT

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DFM(A)- ASPECTS FOR A MICROWAVE WAVEGUIDE RING RESONATOR DESIGN

Keywords: *Manufacturability analysis, design for manufacturing and assembly, microwave mechanics, microwave resonators*

ABSTRACT

In this research manufacturability analysis is made for an E-plane waveguide ring resonator. About the electrical characteristics of the waveguide ring resonator is discussed. Possibilities to utilize concurrent engineering method both for designing and making manufacturability analysis for MW- and RF-components are discussed. For helping to establish the necessary guidelines for easy manufacturing and assembly of the waveguide ring resonator a specialised DFM(A)-questionnaire is generated. The questionnaire gives also new information for collaborative designing approach in MW-/RF- engineering. The advantages and disadvantages of the concurrent engineering design method are evaluated in the research.

CONTENT LIST

1 INTRODUCTION

In this research manufacturability analysis will be made for an E-plane waveguide ring resonator. Possibilities to utilize concurrent engineering-method both for designing and making manufacturability analysis for MW-/ RF -components will be discussed.

For helping to establish the necessary guidelines for easy manufacturing and assembly of the MW-/RF-component a specialised DFM(A)-questionnaire will be generated. The questionnaire gives also new information for collaborative designing approach in MW-/RF- engineering. Also the advantages and disadvantages of the selected design method are evaluated.

Practical guides and instructions for easy manufacturing are collected especially for concurrent engineering. In this report we will focus in researching components, which are made of different aluminum alloys.

This research is part of the EU-project entitled “Collaboration for human resource development in mechanical and manufacturing engineering (Contract: ASIA-LINK -ASI/B7-301/98/679-023). Within the same series of publications belong seven reports, which are focused to following design methods:

- systematic design
- reverse engineering
- concurrent engineering
- cross-technological approach
- collaborative design
- use of integrated product teams
- virtual prototyping

All these seven reports will be published at Lappeenranta University of Technology during the year 2004 in the series of scientific reports of the Department of Mechanical Engineering.

2 THE WAVEGUIDE RING RESONATOR STRUCTURE

The waveguide ring resonator is a component that can be used e.g. as a filter or a building block for multiplexers. Two fundamental types of the waveguide ring resonator structures are H- and E-plane waveguide ring resonators. The H-plane waveguide ring resonator is formed by a circle of a waveguide that is curved in the plane of magnetic field. The E-plane waveguide ring resonator is formed by a circle of a waveguide that is curved in the plane of electric field. Electromagnetic bending of the E- and

H-planes is different and the both structures have their own characteristics. [1] In this reserach, the E-plane waveguide ring resonator is designed by applying concurrent engineering design method. A basic construction of the E-plane waveguide ring resonator structure is presented in Figs 1.1 and 1.2.

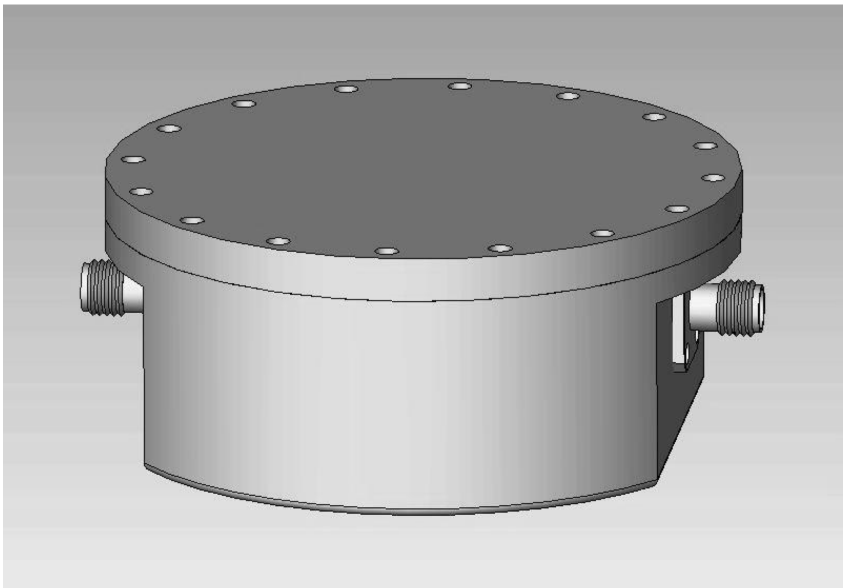


Figure 1.1. The basic construction of the E-plane waveguide ring resonator.

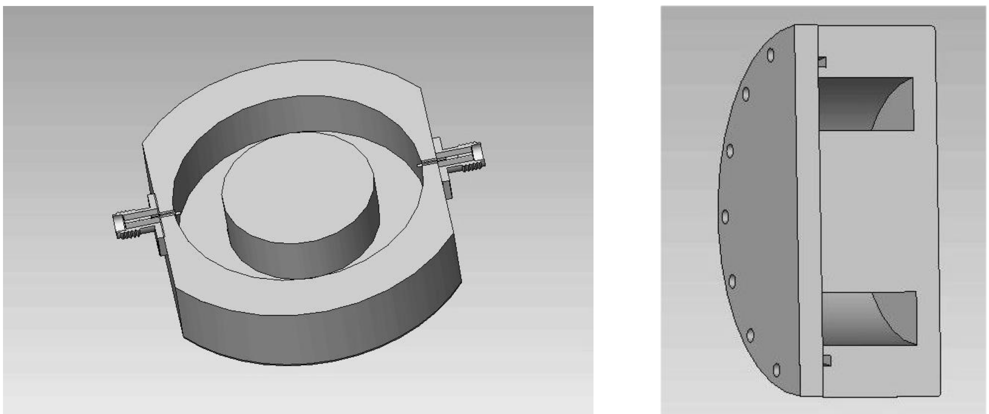


Figure 1.2 Cross-sections of the of the E-plane waveguide ring resonator. The coaxial connectors are used to excitate wave modes to the cavity. The dimensions of the cavity are denoted with *a* and *b* (*a* is the wider side of the cavity and *b* is the narrower side of the cavity). The slot between the cover and the body of the resonator is required for the use of a conductive gasket.

2.1 Function of the E-plane waveguide ring resonator

The E-plane waveguide ring resonator has coaxial to waveguide transitions on the annular sides of the cavity. The coaxial feeds are carried out using standard SMA connectors. The feeds are located symmetrically on both sides of the waveguide ring resonator. The center pin of the SMA connector forms an electric probe and excites TE_{10N} mode to the ring cavity, when the N is the mode number of the annular ring resonator. The waveguide ring resonator structure is a serial resonator. The main resonance frequency or harmonics appears when the mean radius of the ring cavity is equal to the guided wavelength of the waveguide or multiple of the guided wavelength. The main resonance frequency and its harmonics can be calculated by using the following equation:

$$2\pi r = N\lambda_E , \qquad (1)$$

where r mean radius of the waveguide ring cavity

λ_E guide wavelength for the dominant TE_{10} mode in the E-plane

N mode number of the resonator.

Chang et al [1] have presented a mode chart for the four first modes of the resonator. A corresponding mode chart is presented in Fig 2.1.

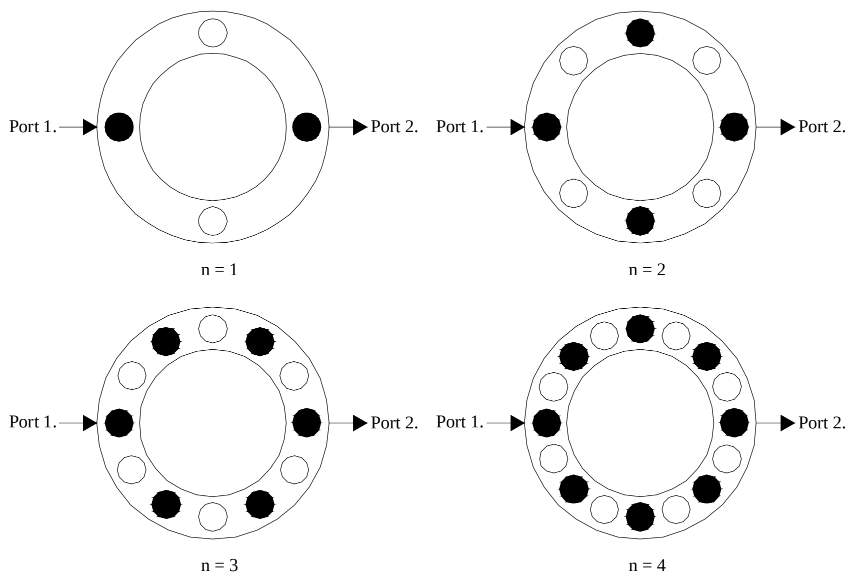


Figure 2.1. The mode chart for the four first modes of the waveguide ring resonator structure. The black circles denote locations of the maximums electric field strengths and the white circles denote locations of minimum electric field strengths.

Lewin et al. [2] has presented a second order correction for the guided wavelength for the waveguide curved in the E-plane. The equation for the second order correction is following:

$$\frac{1}{\lambda_E^2} = \frac{1}{\lambda_g^2}\left[1 - \frac{\left(\frac{1}{R}\right)^2 b^2}{12}\left(1 - \frac{8\pi^2 b^2}{5\lambda_g^2}\right)\right], \tag{2}$$

where λ_g is the guided wavelength in the rectangular waveguide. The guided wavelength in the rectangular waveguide for TE_{mn} modes can be calculated as follows [3]:

$$\lambda_g = \frac{2\pi}{\sqrt{(m\pi / a)^2 + (n\pi / b)^2}}\ , \tag{3}$$

where	a	dimension of the waveguide (wider side-wall)
	b	dimension of the waveguide (narrower side-wall)
	m	mode number of electromagnetic wave
	n	mode number of electromagnetic wave.

The cut-of frequency of the rectangular waveguide can be calculated with the following equation [3]:

$$f_c = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{(m\pi / a)^2 + (n\pi / b)^2}\ , \tag{4}$$

where	a	dimension of the waveguide (wider side-wall)
	b	dimension of the waveguide (narrower side-wall)
	c	speed of light in free space
	m	mode number of electromagnetic wave
	n	mode number of electromagnetic wave
	ε_r	dielectric constant.

2.2 Dimensions of the waveguide ring resonator

The main resonance frequency of the waveguide ring cavity is designed to be 7.7 GHz. The dimensions of the *a* and *b* are selected to be 20.4 and 10.2 mm. The mean radius of the ring cavity is calculated to be 20.9 mm and the cut-of frequency 7.3479 GHz.

2.3 Losses of the waveguide ring resonator

The losses of the waveguide ring resonator are formed mainly due to the conductor losses. The resonator cavity is filled with air, thus there is no dielectric losses. The conductor losses for the rectangular waveguide and TE_{mn} mode can be calculated by using the following approximations [3]:

$$Rs = \sqrt{\frac{\omega\mu}{2\sigma}} \tag{5}$$

$$\alpha_c = \frac{R_s}{a^3 b\beta k\eta}(2b\pi^2 + a^3k^2), \tag{6}$$

where
- R_s surface resistivity of the waveguide material
- ω angular frequency
- μ permeability of the waveguide material
- σ electrical conductivity of the waveguide material
- β propagation constant
- k wave number
- η wave impedance.

In addition, effects of surface roughness of the waveguide cavity must be taken into account by using Morgan's experimental equations [4]. Hammerstad et al. [5] have made more practical notation about Morgan's equations.

2.4 Requirements of electrical characteristics

Requirements of electrical characteristics of the designed waveguide ring resonator structure are presented in table 2.1.

Table 2.1. Electrical requirements for the waveguide ring resonator.

Main resonance frequency	7.7 GHz
Second harmonic resonance	15.4 GHz
Value of the unloaded quality factor	At least 1000

3 CONCURRENT ENGINEERING DESIGN

3.1 Introduction to concurrent engineering design

Concurrent Engineering Design (CE Design) is a term that formally describes a set of technical, business, manufacturing planning, and design processes that are concurrently performed by elements of the manufacturing organisation. The CE Design process, in its simplest form, is the integrated execution of four businesses and technical processes at the same time. These processes are

a) Process Management,
b) Design,
c) Manufacturability care, and
d) Automated Infrastructure Support.

Fig. 3.1 illustrates schematically the basic difference between the traditional design philosophy and concurrent engineering design.

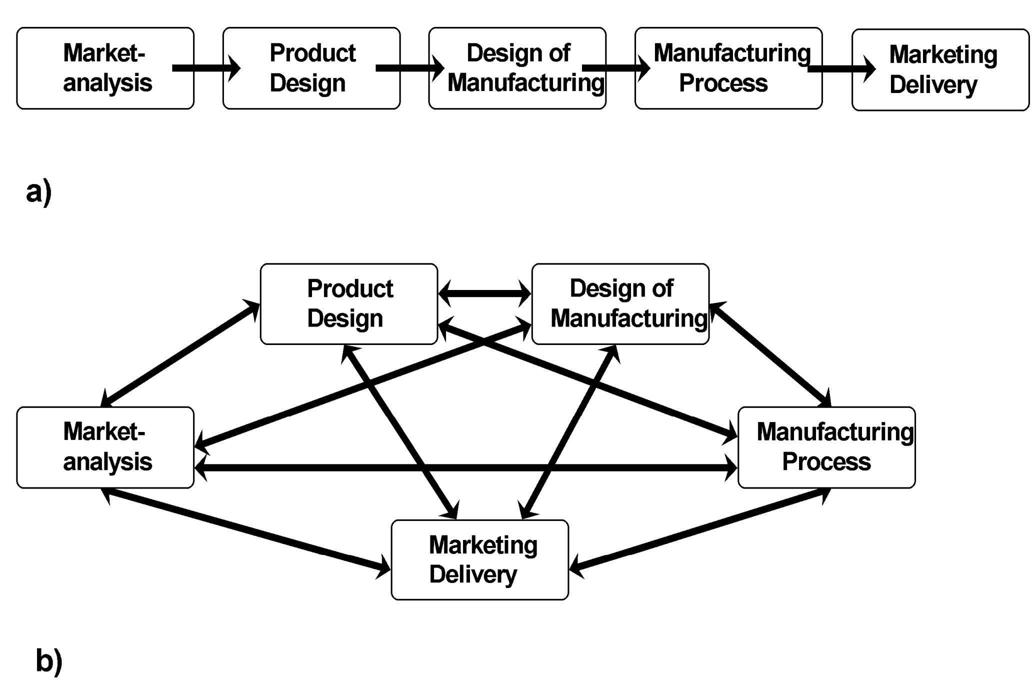


Figure 3.1. Schematic presentation for a) traditional design and b) concurrent engineering design [7].

There are at least three different terms in the literature that are meant to refer to the same subject: concurrent engineering (CE), simultaneous engineering (SE) and parallel engineering. Also the term "integrated product development" is used.

The main purposes of concurrent engineering are the reduction of developing time and costs, an improvement of quality and the enhancement of competitiveness. However, at least the following aspects have been underlined within a CE based design process:

- Importance of process management

- Importance of production management issues
- Need of Life Cycle Analysis (LCC) to support designer's decision-making process
- Use of quality-oriented decision making during concurrent engineering process
- Lack of methods supporting the planning of production systems when using concurrent engineering
- Improper understanding how to tailor the concept to suit different circumstances e.g. in various kinds of companies
- Importance of the human, organisational and social aspects in the working team

So-called collaborative-concurrent design is an effective process for CE Design. It uses on a holistic basis. Manufacturability, production planning and incorporation are not added steps, but an integral part of the process. In collaborative-concurrent design, the fully designed end-product (construction) comes out simultaneously. Design variants can be considered quickly, and the cycle-time, costs, and quality disadvantages of a step-wise refinement can be largely avoided.

Manufacturability can be regarded as a special process within CE Design. It is focused at the transition of the product and process design towards total production management. This particular change in perspective has created the “wall” between designers and the rest of the complex modern manufacturing organisation. Teaming is an important element of CE Design and becomes particularly important in discussions of manufacturability. The various areas of production affected by different design aspects are indicated as members of the Concurrent Engineering (CE) dimension of the CE Design Team. The simultaneous interest of design and manufacturability makes up the CE Design. The transition from design to manufacturability is also reflected in the interaction of different CE Design intellectual activities. As the initial product outlines, general specifications, and component strategies are developed during conceptualisation, production planning begins. As more details come up in visualisation, more detailed product and component production scheduling, material acquisition, and other details of planning are conducted. [6],[7]

3.2 About the suitability of CE for MW-design

Common requirements for an effective design method are as follows:

1. The method must be applicable to every type of design activity, no matter in which specialist field.
2. The method should facilitate the search for optimum solutions.

3. The method should be compatible with the concepts, methods and findings of other disciplines.
4. The method should not rely on finding solutions by chance.
5. The method should facilitate the application of known solutions to related tasks.
6. The method should be compatible with electronic data processing.
7. The method should be easily taught and learned.
8. The method should reduce workload, save time, prevent human errors, and help to maintain active interest.

A very simple way to estimate product's manufacturability is to use the following four items:

1. Binary measures (whether or not a specific manufacturing method is suitable)
2. Qualitative measures (products can be classified according to their manufacturability e.g. into groups ”poor”, ”average”, ”good” or ”excellent”)
3. Abstract quantitative (some numerical index is counted to describe product's manufacturability)
4. Time and cost comparison

If the design method does not include any of these check points in the early stages of the design process, obviously the method is not too effective for DFM(A)-analysis.

In many cases it is possible to divide the research area of design method into a function-oriented, a performance-oriented or a manufacturability-oriented product design. Alternatively various approaches can be developed for customer-oriented, quality-oriented, cost-oriented and organisation-oriented design.

The real need for improvements is between these two extremes. This means that the effective method for the designers should not be too limited (like in the performance-oriented design) or too general (like in the organisation-oriented design), but it should, however, include the context of design environment. That is why the traditional design methods are improved for specific design tasks, e.g. for MW- and RF-component or system design.

In MW-mechanics the idea of teaming, CAD-integration and VE have proved to be effective in those cases where the design group consisted of experts on electronics, engineering design, sheet metal work and laser processing. All the microwave mechanics and associated components, jigs and fixings could be 3D-modelled to ensure both the functional and geometrical requirements as well the manufacturability aspects. Especially the needs of structural changes for some specific manufacturing technologies are easy to obtain by using 3D-modelling during the early stages of design process.[6],[7]

3.3 About the suitability of CE for the waveguide ring resonator design

The assembly of the waveguide ring resonator structure consist of three main components; the ring cavity, the cover and the SMA connectors. The concurrent engineering design method is noted to be efficient in conjunction of the design of the waveguide ring resonator. Manufacturability aspects, possibility of automated infrastructure support, economical aspects and microwave design aspects have been used in the design procedure at the same time. For example the inner and the outer dimensions of the ring cavity have been selected by using following aspects:

a) Requirements of microwave characteristics, e.g. resonance frequency
b) Manufacturability of the cavity by using machining
c) Economical aspects e.g. thickness of walls selected to be identical to the length of the extended dielectric of standard SMA-connector
d) Possibilities of automated infrastructure support, e.g. design the mounting properties of the cover to enable automated assembly of the cover

The mechanical 3D-modeling during the design process is used to ensure possibility of assembly of all parts and also to eliminate possible double-tolerancing of the cover and the cavity assembly. Additional requirements for the waveguide ring resonator from the market analysis can be also used to define properties of the ring cavity, SMA connectors and all the structure. If customers would like to use other connector types than SMA in the coaxial to the waveguide transition, the properties of substitutive connector type could be taken into account and both advantages and disadvantages of the choice will be utilized in the design for manufacturing. The authors recommend the use of concurrent engineering method for design of waveguide components.

4 DFM(A)-QUESTIONNAIRE FOR THE COMPONENT

4.1 General instructions to generate the questionnaire

To help to establish the special requirements of the MW- or RF-component it is possible to generate a questionnaire, which could be modified from the general presentation shown in table 4.1. The basic idea is to collect those design aspects, which will later affect on mechanical design and from which the final requirements for design can be derived.

Table 4.1. A preliminary questionnaire for helping to form the requirement list of mechanical microwave subassemblies [7].

Question	Answer
1. What is the expected operating frequency?	_____ GHz
2. What is the required relative bandwidth?	_____ %
3.What is the maximum radio frequency power to be handled?	_____ dBm
4. Is the unit for a) receive (RX), b) transmit (TX) or c) both?	a) b) c)
5. What is the absolute maximum attenuation allowed?	_____ dB
6. Are semiconductor components involved in the design?	yes no
7. Is the preferred transmission line a) waveguide b) planar c) coaxial d) dielectric?	a) b) c) d)
8. Should the connection to adjacent modules go a) through coaxial connectors or b) waveguide flanges or c) none?	a) b) c)
9. Is the unit a) sealed for life or b) should there be a possibility for service & repair?	a) b)

One example to show how this table guides the design process: if the expected operating frequency of the device is lower than 1 GHz, generally any material could be used and dimensional tolerances can be even > 1 mm. If the operating frequency is < 15 GHz, most metals are acceptable, including steel but oxidation is to be avoided, surface and alignment tolerances should be generally < 0.1 mm. And finally if operating frequency is over 15 GHz, only highly conductive metals (Cu, Au) can be used, most impurities are extremely harmful, and tolerances should be even better than 5 – 10 µm.

Typically the questionnaire presented in table 2.1 should be filled by a MW-/RF-engineering expert. For specific designs some additional questions might also be useful. Expert of manufacturing technologies is needed to generate the questionnaire for a specific manufacturing stages to ensure products DFM(A)-aspects. A lot of background information is needed to manage to present the right questions to the designer. However, the designer is the only expert who is able to explain the limits or restrictions due to functional aspect of the product for different manufacturing operations. Example of a questionnaire, which is made especially for a laser-processed product, is presented in table 4.2. Depending on each possible manufacturing technology for the product's geometry, several questionnaires should be generated and filled in.

Table 4.2. Special DFM – questions for laser processing, illustrative examples [7].

Question	Implementation
1. Are the possibilities to use the fixing systems for machining considered? (typically the requirements of accuracy of fixing in laser processing and machining are almost equal)	yes no
2. Could the carbon content of steel be kept under 0.2 % (or at least not higher than 0.3%)?	yes no
4. Are the joint preparations for laser welding documented including necessary tolerances and manufacturing methods? (laser cutting or machining are recommended, however R_a < 12,5µm is appropriate)	yes no
5. Are butt welds with raised edges or lap joints with seam welds used whenever it is possible due to constructional aspects?	yes no
6. Are more than two plates welded with the same (seam) weld whenever it is possible due to constructional aspects?	yes no
7. Is the construction possible to be laser processed from one direction or at least in one plane?	yes no
8. Are the values for air gap and allowed misalignment marked in the design documents (for example: butt joint/air gap 0.15 mm ,t<10 mm, misalignment<0.3 mm)	yes no
9. If the material's hardenability properties must be taken into consideration, are the most appropriate joint geometry utilised? (for example the weld is placed mostly on the plates to be welded)	yes no
10.If wires or strings are welded, are the most appropriate joint types used? (power density should be dealt equally to the parts to be joined)	yes no
11.If jigs are needed, are the fixings of jigs designed and marked on the drawings? (in case when the workpiece is moving in front of the beam)	yes no
12.Is the need for grinding the reinforcement marked in the drawings if several sheet metal constructions are welded together?	yes no
13.When jigs are needed for welding partially closed structures, is the possibility of shrinking taken into account when removing the workpiece?	yes no
14. Is the possibility to use various material combinations considered?	yes no
15.Are the possibilities to use different laser processing methods for the same construction or multi-processing methods considered?	yes no
16. Are the points were laser welding starts and ends designed to meet quality aspects?	yes no
17.Is the CAD-geometry of the workpiece saved in the DXF-format (or any other suitable) for CAD/CAM-integration?	yes no
18.Are the traditional instructions for designing sheet metal parts taken into account? (needed for example for cut-bend-weld multi-processing)	yes no
19.Are the adjusting holes or fits marked on the drawings? (or are other additional geometries necessary for adjusting the parts together)	Yes no

In general the list of actions to put DFM(A) in practice is relatively simple:

- minimise the number of parts in a construction
- design modular constructions
- try to find as many functions for a part as possible
- avoid additional components for joining other parts
- design the construction so that all the parts can be assembled from the same direction
- minimize the number of different manufacturing methods and stages to be used
- obey the rules of easy manufacturing for each manufacturing method (applied into your own production)

- check that there is enough space for necessary tools during assembly, fixing systems during manufacturing and a robotic gripper in automated systems
- use standardised geometry, tools and components
- check the machining allowances
- check the suitability of the material for the manufacturing methods
- use appropriate general tolerances for your own production
- check the summarised errors of the assembly and design a harmless place for manufacturing errors in the construction
- check that the values of surface roughness, tolerances for linear and angular dimensions and geometrical tolerances are adjusted together
- use parts which can be assembled from several directions and still function perfectly (avoid parts which easily assembled in wrong a position or which function only in one position)
- if there are several possible manufacturing methods choose the one, which needs least preparations
- try to repeat the same manufacturing stages, think that each manufacturing stage is also ”a module”
- use parametric design
- design the products directly for automated production (in most cases they will be extremely well suitable for manual production too)
- if manual production is used check the ergonomic aspects

4.2 Special questionnaires for the component and for machining

During different design stages this list can be used as a checklist to ensure that manufacturability aspect have been taken into account. Special questionnaires for the component and for machining are presented in tables 4.3 and 4.4.

Table 4.3 Special questionnaires for the component.

Question	Answer
1. What is the expected operating frequency?	7.7 GHz
2. What are frequencies of the required harmonics?	15.4 GHz
3. What is the expected unloaded quality factor?	1000
4. Is the preferred transmission line a) waveguide b) planar c) coaxial d) dielectric?	a)x b) c) d)
5. Should the connection to adjacent modules go a) through coaxial connectors or b) waveguide flanges or c) none?	a)x b) c)
6. Is the unit a) sealed for life or b) should there be a possibility for tuning?	a) b)x

Table 4.4. Special DFM – questions for machining.

Question	Implementation
1. Are the possibilities to use the fixing systems for machining considered?	yes x no
2. Is the workpiece and order of various manufacturing stages designed so that repeating of the fastening cycles is avoided	yes x no
3. Is the workpiece long, thin or flexible?	yes no x
4. Is the selected material classified as "difficult to machine"	yes no x
5. Is the possibility to use various material combinations considered?	yes x no
6. Is the CAD-geometry of the workpiece saved in the DXF-format (or any other suitable) for CAD/CAM-integration?	yes x no
7. Is the possibility to use standardized stools considered?	yes x no
8. Is the construction possible to be manufactured by turning?	yes x (partly) no
9. Is the volume of material to be removed tried to be minimized in the design?	yes x no
10. Is it possible to use milled outer chamfers for replacing round geometries?	yes x no
11. Is the corner radiuses of milled inner geometries selected according to the standardized stools?	yes x no
12. If the designed component includes a closed cavity, are there enough place for using tools for different required machining processes	yes x no
13. Is the remark of the required cleaning instructions included to the documentation of the workpiece.	yes x no
14. Are the requirements for the surface quality remarked	yes x no
15. Is the requirement for $R_a < 0.8\mu m$	yes no x

5 REQUIREMENT LIST FOR THE WAVEGUIDE RING RESONATOR

This research is focused to the ring resonator design. Resonator body is made of AlMg3 aluminium alloy. AlMg3 is easy to machine and it does not require any plating. AlMg3 can be plated with silver if lower losses are tried to achieve.

Basically the ring resonator is a cylindrical cavity, which could be manufactured e.g. by machining. Construction includes also standard SMA connectors (Johnson Components, type 142-1701-191). Basic resonator geometry is presented in Figs 1.1 - 1.2.

5.1 General requirements

<u>Geometry</u>

Ring resonator's inside dimensions are calculated to match the required performance. On the other hand the connector's assembly require specialised geometries from the body. Also the assembly of the resonator itself requires specialised joining data. All the required dimensions of the resonator structure are presented in the appendices.

Forces
It is required that the resonator structure can withstand the maximum tensile load allowed for the cables, which will be joined with the connectors. The maximum allowed tensile load for the cable is 270 N.

Environment
This resonator can be easily used at wide temperature ranges. The required environmental requirements at this research are as follows:

- temperature range 15 – 50 ˚C
- relative humidity range up to 50 %.

Safety and ergonomics
To ensure the easy manufacturing of geometry the required space for mounting screws must be checked. There must also be enough room for using the special tool for tightening the threaded connection of the cable.

Production
During this research we will focus to different machining technologies to be able to produce a small series of ring resonators. Materials machinability is therefore in key-role. On the other hand we must ensure that there will be enough space for machining tools. It should also be possible to use necessary fixing systems and jigs during various manufacturing stages. This aspect will be discusses in chapter 6 in details.

Quality control
The quality of the resonator could be measured by analysing its performance by using scattering parameter measurements. The scattering parameters can be measured using a network analyzer. The resonance frequencies, quality of matching and losses of the resonator can be calculated by using the scattering parameters.

Assembly
The SMA-connectors for cable connections are assembled to the waveguide resonator by using four M2.5×3 screws. The tightening moment for those screws is 0.45 Nm based on the earlier experiments. The tightening moment for the cable connection is 0.9 Nm according to the standards of the connector.

Recycling
Resonator body is made of AlMg3 and it could be re-used. The bodies of SMA connectors are made of brass and can be recycled. Also the insulation material of the connectors can be re-used.

Costs

During industrial manufacturing special automated machines are used for resonator body production. When specialised resonators are manufactured, main costs consists of three main aspects:

- production of the required CAM-data for machining
- manufacturing and quality control of geometries inside the cavity
- assembly of components (cover, connectors etc.)

5.2 Electrical requirements

Specialised electrical requirements for the material of the resonator are presented in table 5.1.

Table 5.1. Electrical requirements for the construction material.

Influencing factor	Material characteristics	Required value
Skin depth	Relative permeability	1
	Electrical conductivity	> 2.0 $\cdot 10^7$ [S/m]

5.3 Requirements for geometric tolerances

To ensure resonators high performance, the geometry and the dimensions of the cavity inside the body are critical. To ensure the quality of the component either circularity, cylindricity or concentricity of the cavity should be required (see Fig. 5.4).

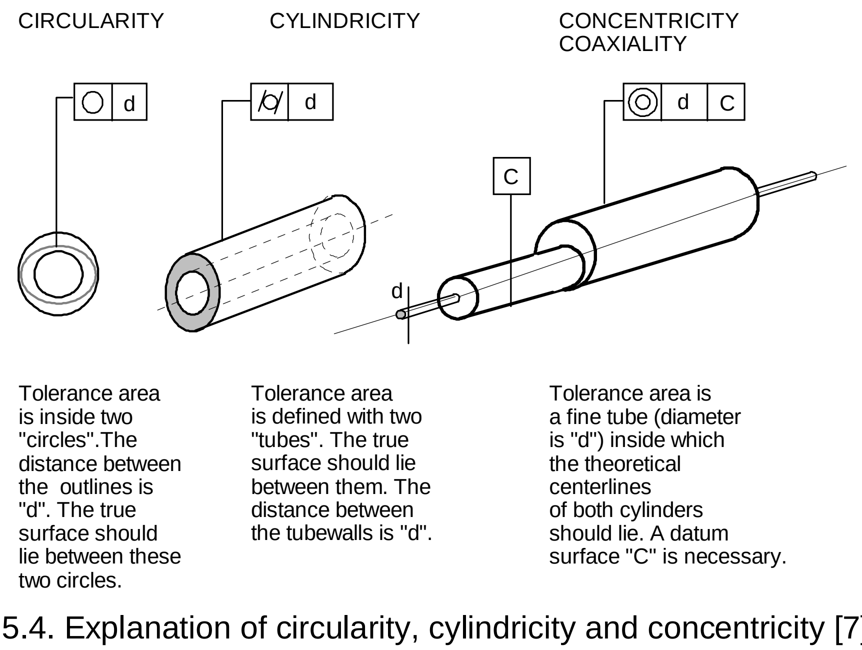


Figure 5.4. Explanation of circularity, cylindricity and concentricity [7].

Numerical estimation for the required dimensional and geometric tolerances could be estimated from table 5.2 according to the operating frequency range. However, the fittings between the body and the cover or between the body and the insulating elements of the connectors should be selected more likely according to functional properties of the joints. What is even more important to note here to ensure a proper assembly with standardised components, we should require those deviations of the dimensions, which are presented in e.g. standard sheets of connectors. [6],[7]

Table 5.2. Estimation of the required tolerance grade according to the operating frequency [7].

Frequency (GHz)	**Surface roughness**	**Tolerance grade**
300-600	0.8 μm	IT5
150-300	1.6 μm	IT6
75-150	3.2 μm	IT7
35-75	6.4 μm	IT8
15-35	12.8 μm	IT9-10

Effects of different tolerance grades of surface roughness to the conductor losses of the waveguide structures and designed waveguide ring resonator structure are presented in Figs. 5.5 - 5.7.

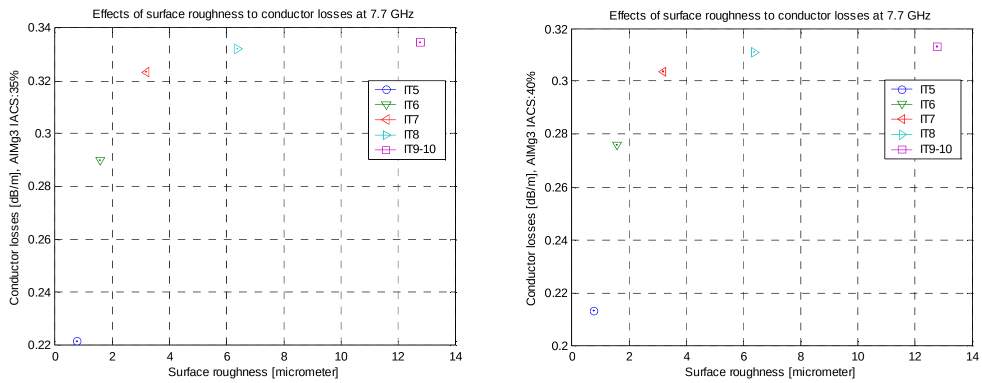


Figure 5.5. Effects of the surface roughness to the conductor losses [dB/m] of the rectangular waveguide constructions at 7.7 GHz frequency. (Materials AlMg3 IACS 35% and 40%. Dimensions of the waveguide: *a*=20.4 mm and *b*=10.2 mm.)

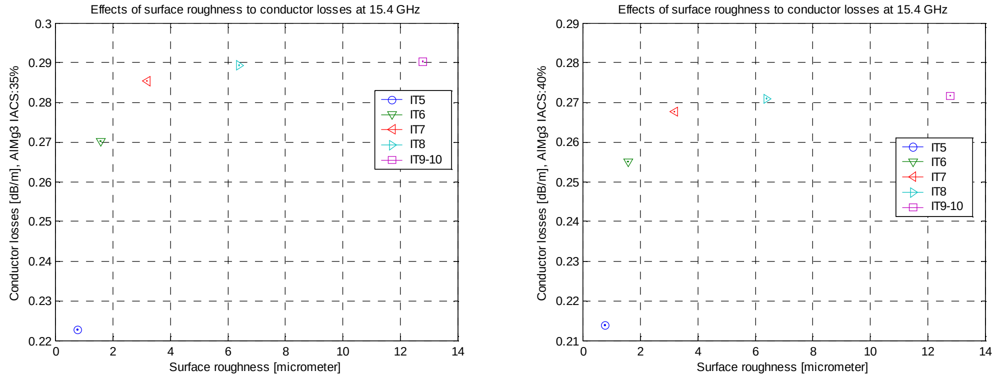


Figure 5.6. Effects of the surface roughness to the conductor losses [dB/m] of the rectangular waveguide constructions at 15.4 GHz frequency. (Materials AlMg3 IACS 35% and 40%. Dimensions of the waveguide: *a*=20.4 mm and *b*=10.2 mm.)

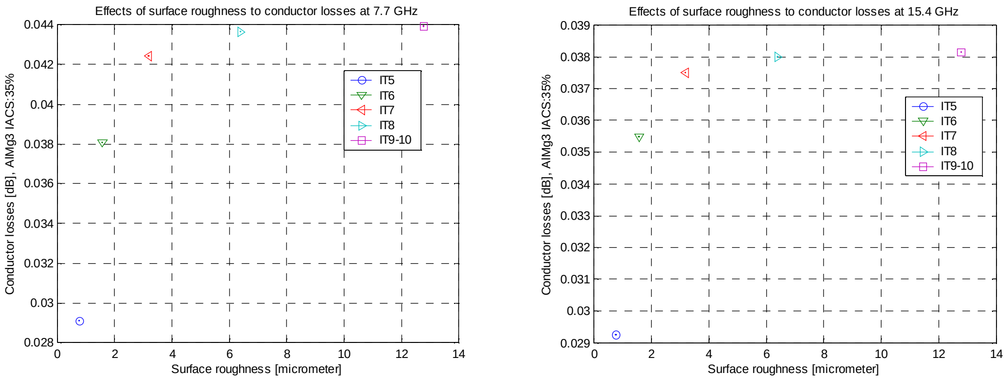


Figure 5.7. Effects of the surface roughness to the conductor losses [dB] of the designed waveguide ring resonator structure at 7.7 GHz and 15.4 GHz frequencies (IACS:35%).

The following mechanical properties of the waveguide ring resonator are essential for achieving high performance:

- surface roughness of inner surfaces of the cavity
- sealing properties of the cavity
- positioning accuracy of the connectors
- the actual meanradius of the ring cavity
- maximum allowed distance between the possible mounting screws of the cover
- straight edges of the cavity region
- uniform shapes of the excitation rods.

6 ALTERNATIVE MANUFACTURING TECHNOLOGIES

The design and DFMA study were mostly carried out for machining technologies. The modern quality management technology of CNC-machines gives the possibility to control e.g. tool wearing and machining parameters. Thus, by using the high-accuracy milling process for manufacturing the parts of the resonator, it is possible to ensure that no under sized dimensions are allowed. This means that the milled dimensions are inside the positive allowed deviations of the selected tolerance grade. The construction of the resonator can be designed so that either the accumulation of manufacturing deviations is positive or equal to zero. For these reasons it is more appropriate to describe the probability of manufacturing accuracy by using Weibull-distribution instead of normal distribution. The distributions of the manufacturing accuracy can be used to support system design by substituting the results of the probability analysis into the design functions of the waveguide ring resonator. [8]

An alternative manufacturing technology for the waveguide resonator structure is the high pressure casting. The AlMg3 aluminium alloy is available for both casting and machining. The utilization of high-pressure casting requires dies and models. Thus all dimensional or geometrical changes in the construction require new dies and models. A cost-effective high-pressure casting can be achieved with large-scale manufacturing batches. An additional polishing stage is required in conjunction of the high-pressure casting technology. The polishing stage can be required also for machined components.

6.1 Machining of the waveguide resonator structure

The machining stages of the body of the waveguide resonator are presented in Figs 6.1 - 6.6. Photos of tools are taken from [9].

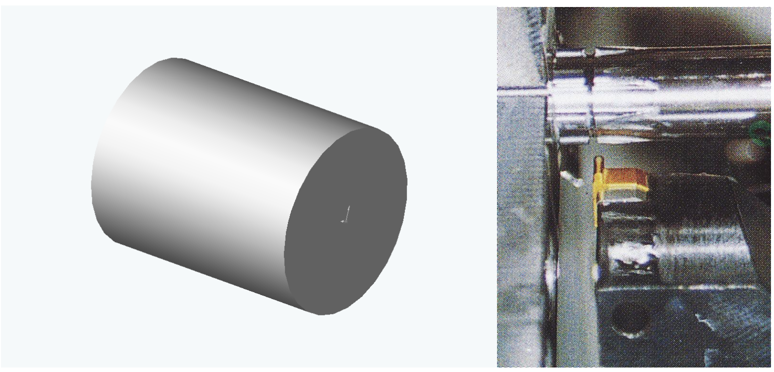


Figure 6.1. Stage 1: Cutting a suitable billet of a round bar.

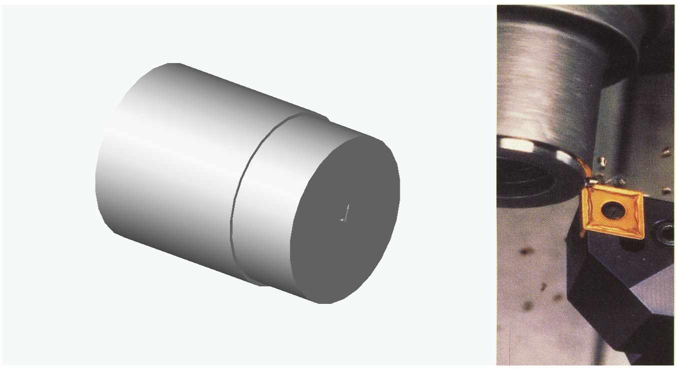


Figure 6.2. Stage 2: Turning the outer diameter of the body if the diameter of the pillet cannot be chosen to be equal to the outer diameter of the cavity.

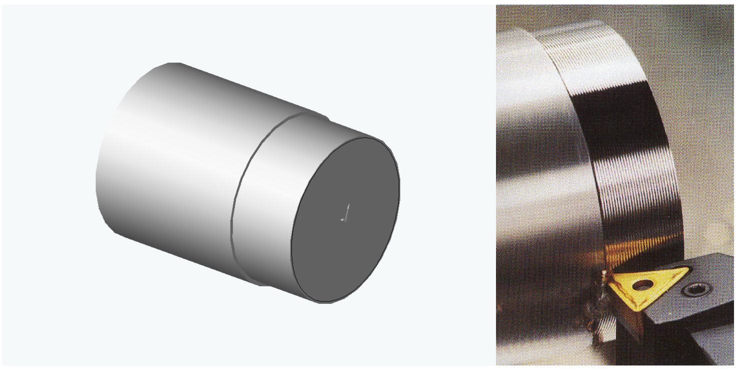


Figure 6.3. Stage 3: Turning the threads for the assembly of the cover.

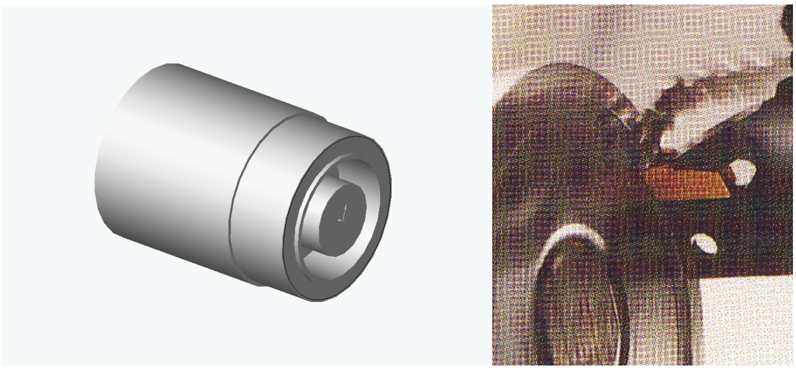


Figure 6.4. Stage 4: Face turning, turning of the cavity.

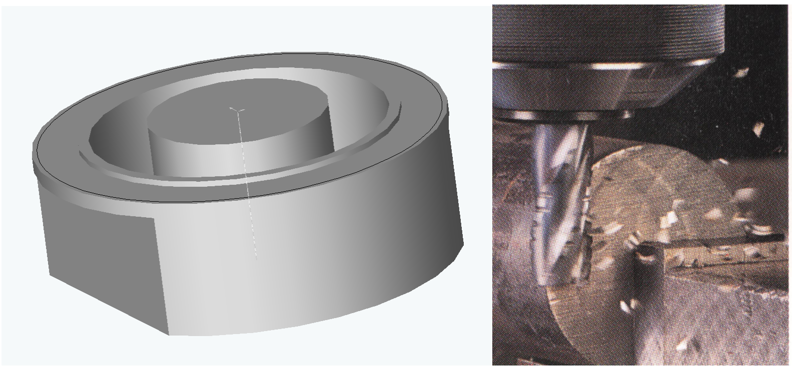


Figure 6.5. Stage 5: Removing the workpiece and milling the outer geometry.

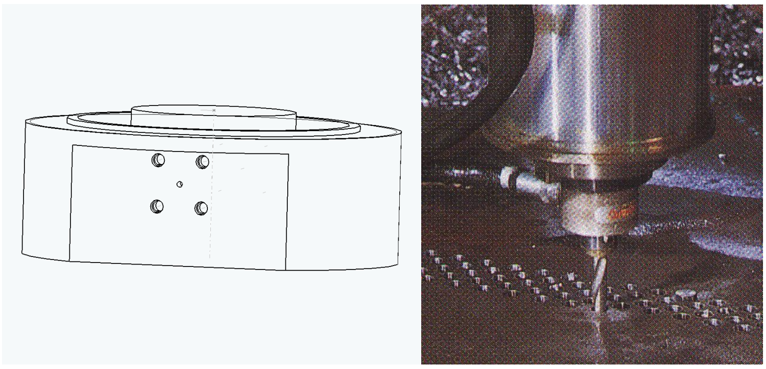


Figure 6.6. Stage 6: Drilling of the holes and making the threads for the connectors.

The machining stages of the cover of the waveguide resonator are presented in Figs 6.7 - 6.12. Photos of tools are taken from [9].

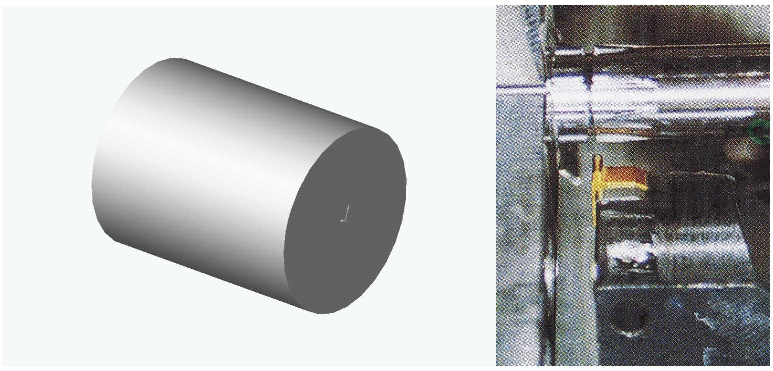


Figure 6.7. Stage 1: Cutting a suitable billet of a round bar.

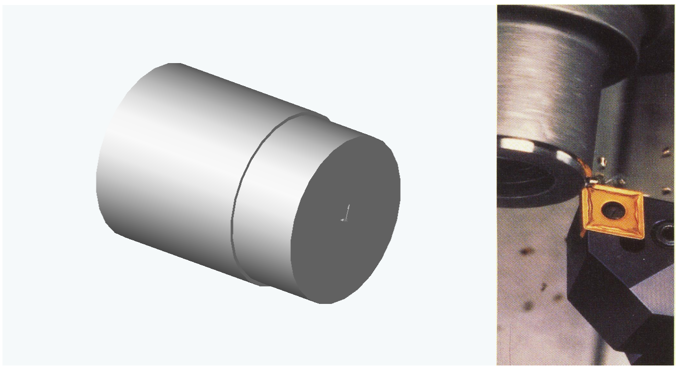


Figure 6.8. Stage 2: Turning the outer diameter of the cover if the diameter of the pillet cannot be chosen to be equal to the outer diameter of the cover.

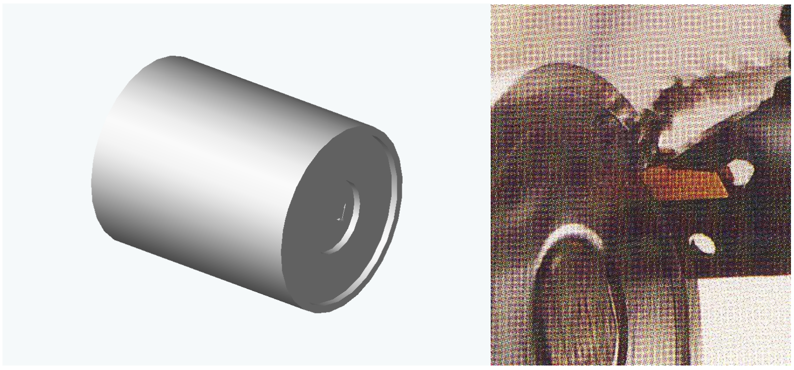


Figure 6.9. Stage 3: Face turning.

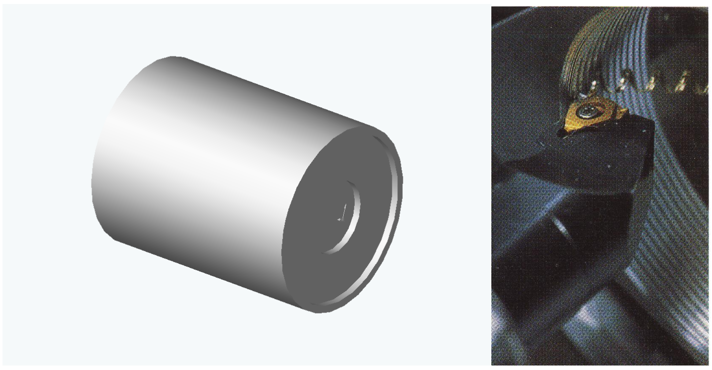


Figure 6.10. Stage 4: Turning the threads for the cover.

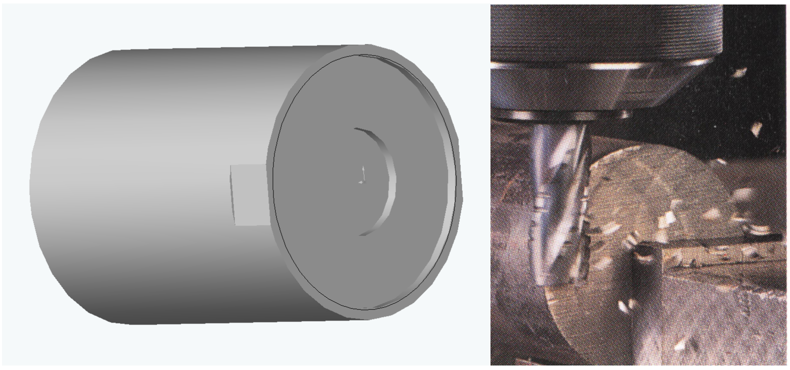


Figure 6.11. Stage 5: Milling outer geometry of the cover.

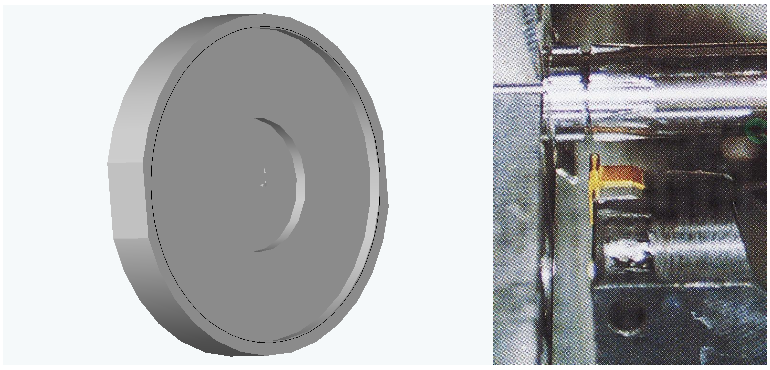


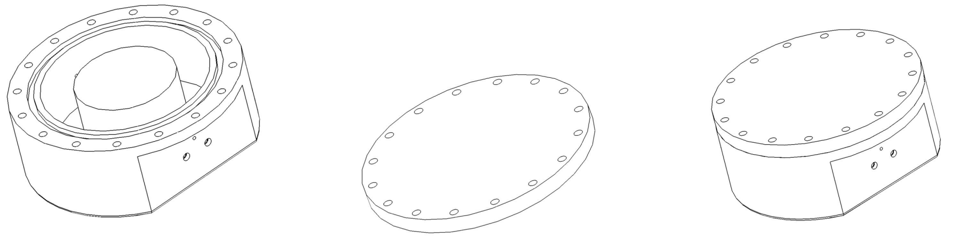
Figure 6.12. Stage 6: Cutting the workpiece.

7 APPLIED DFM(A)-ASPECTS

7.1 Changes of the construction and the geometry

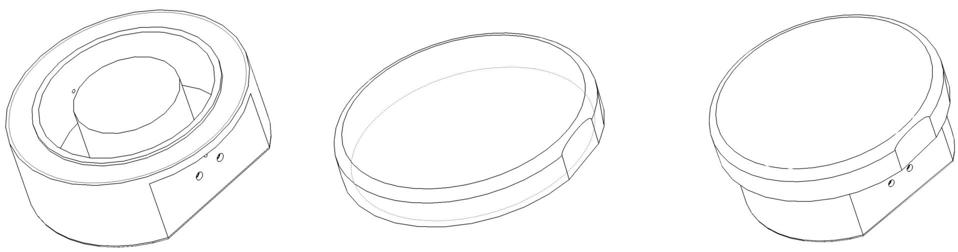
Several changes were carried out for the original construction of the waveguide resonator. The changes were designed to improve the manufacturability and assembly of the parts. In addition number of required parts was minimized. The first modification was elimination of 16 screws, which were originally designed to be used for the assembly of the cover. That was carried out using threads on the cover and the body. By using the threads and suitable geometry also the requirement of a separate conducting seal was eliminated. The possible double tolerancing was avoided by using a hollow on the inner surface of the cover. Also unnecessary chamfers were eliminated from the design to improve the manufacturability of the component. The changes of the construction and geometry are presented in Figs 7.1 and 7.2.

The first designed structure



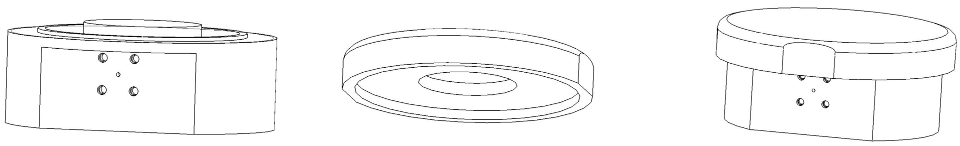
a. The body of the resonator *b. The cover of the resonator* *c. The assembly of the cover and the body*

The designed structure after the first modifications



d. The body of the resonator *e. The cover of the resonator* *f. The assembly of the cover and the body*

The structure after the elimination of the possible double tolerancing



g. The body of the resonator *h. The cover of the resonator* *i. The assembly of the cover and the body*

Figure 7.1. The changes of the construction and geometry for improving the manufacturability.

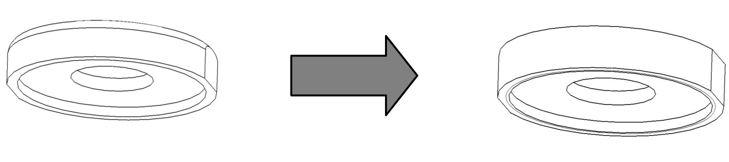


Figure 7.2. An example of elimination of the unnecessary chamfers.

7.2 Choosing more acceptable material

The selected material for the resonator construction is AlMg3. AlMg3 is easy to machine and there are no requirements for surface coating. AlMg3 is available in multiple different standard profiles. Other suitable aluminium alloys are at least AlMgSi1, ALUMEC89 and ALUMEC99. AlmgSi1 provides better electrical characteristics than AlMg3. The electrical characteristics of ALUMEC alloys are better than electrical characteristics of AlMgSi1. AlMg3 was selected because both its mechanical and electrical properties are suitable for the application of this research.

Both ALUMEC 89 and 99 are high strength aluminium alloys. Machinability of ALUMEC 89 and 99 is excellent and stability of the material provides minimal deformation during and after the machining. In addition, high thermal conductivity of ALUMEC enables a possibility to use less complicated cooling systems during the machining. ALUMEC99 provides significantly improved corrosion resistance compared to other ALUMEC types [10],[11]. A comparison of properties between different aluminium alloys is presented in table 7.1.

Table 7.1. Comparison of properties of some aluminium alloys [7],[10],[11],[12].

Material	AlMgSi1	AlMg3	ALUMEC89	ALUMEC99
Conductivity [%IACS]	41 - 55	35 - 40	26.5	26.5
Relative permeability	1	1	1	1
CTE [ppm]	$23.40 \cdot 10^{-6}$	$23.70 \cdot 10^{-6}$	$23.43 \cdot 10^{-6}$ (at temperatures 20–100 ºC)	$23.43 \cdot 10^{-6}$ (at temperatures 20 – 100 ºC)
Penetration depth at 1 GHz frequency	3.26 µm (IACS 41%)	3.53 µm (IACS 35%)	4.06 µm (IACS 26.5%)	4.06 µm (IACS 26.5 %)
Penetration depth at 10 GHz frequency	1.03 µm (IACS 41%)	1.12 µm (IACS 35%)	1.28 µm (IACS 26.5%)	1.28 µm (IACS 26.5%)
Modulus of elasticity [kN/mm^2]	70.0	70.0	70.87	70.87
Density [kg/dm^3]	2.70	2.66	2.82	2.82
Requirement for surface treatment	no	no	no	no

7.3 Detailed changes of dimensioning and tolerances

The thickness of the side walls of the waveguide ring resonator was selected to be identical to the length of the extended dielectric of the selected standard SMA connector (Johnson Components, type 142-1701-191). The mounting of the SMA connector was designed to be carried out with standard screws M2.5X3. The material of the screws is galvanized iron. Dimensions and geometry of the selected SMA connector is presented in Figs. 7.3 and 7.4.

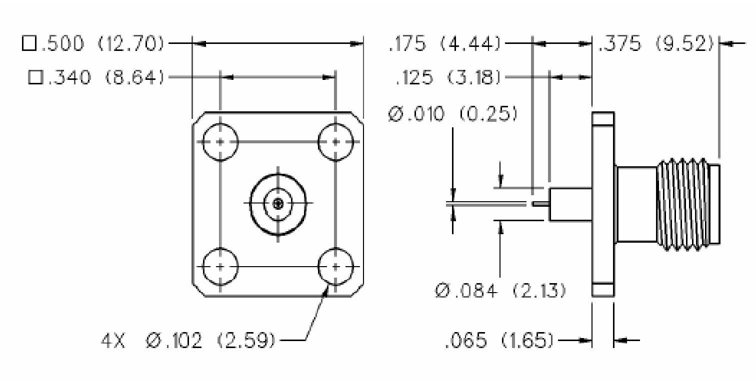


Figure 7.3. The dimensions and geometry of the selected SMA connector. [13]

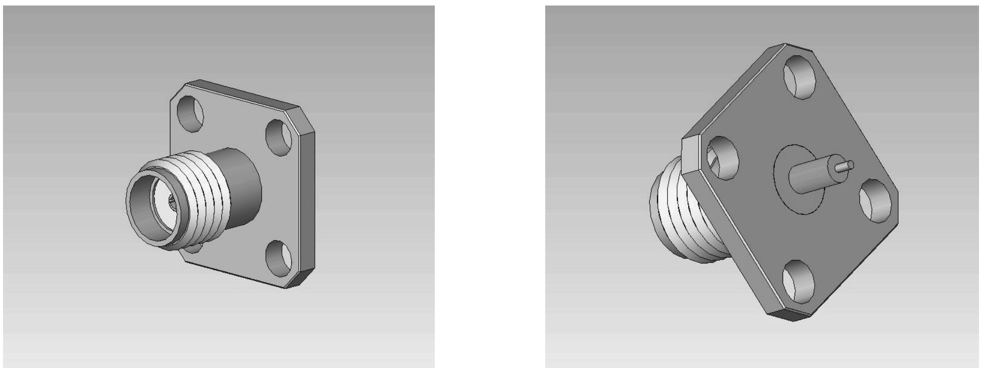
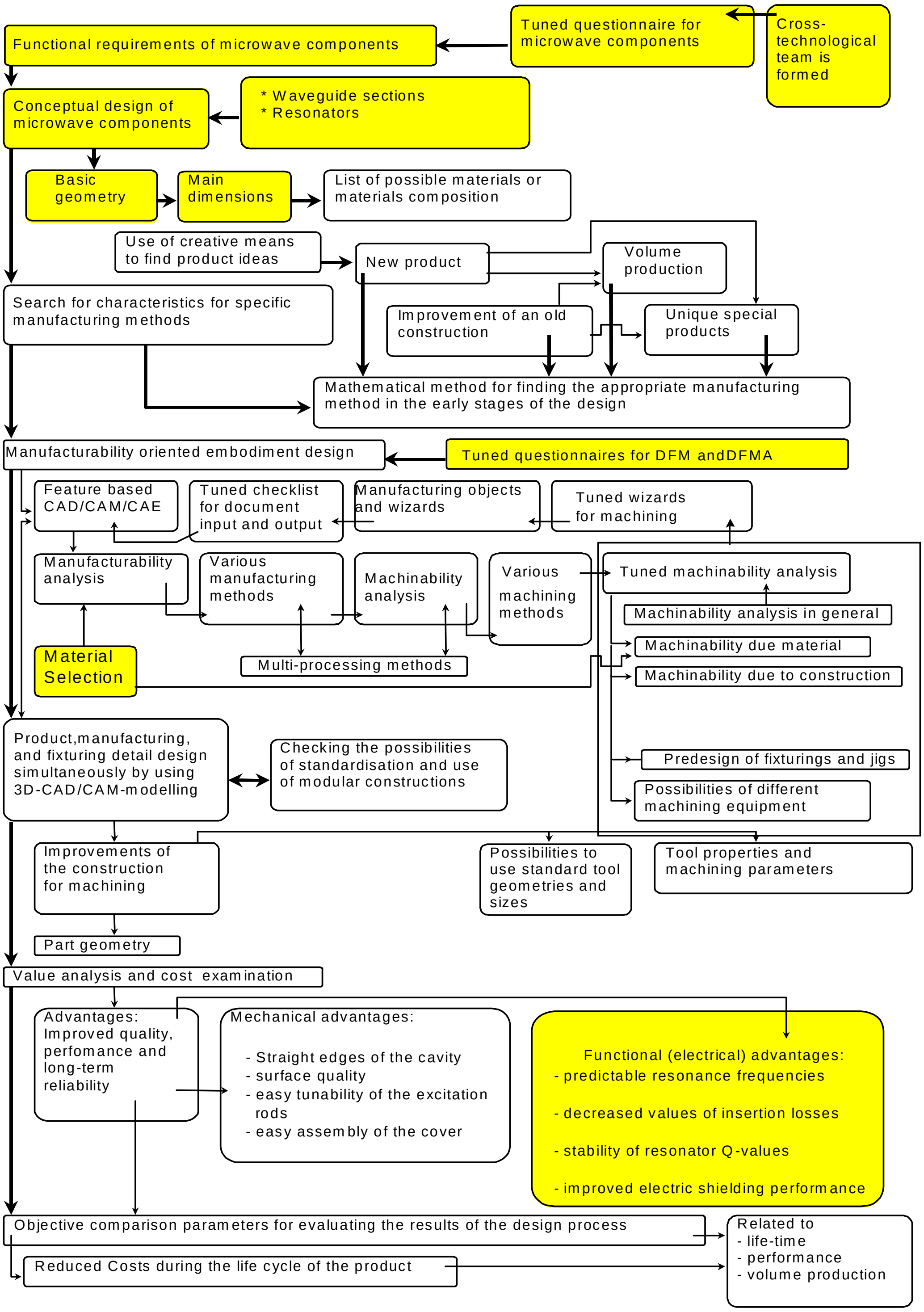


Figure 7.4. The geometry of the selected SMA connector.

The shapes of the resonator was selected for machining by using standard milling and turning tools. The required bulk size was marked to the manufacturing documents and selected according to the standard sizes. The allowed ”open dimensions” for manufacturing inaccuracy and allowed dimensional deviations were indicated in the design.

8 FLOW CHART OF THE DESIGN AND MANUFACTURING STAGES



9 COSTS ASPECTS OF THE WAVEGUIDE RING RESONATOR DESIGN AND MANUFACTURING

Basically there are four main cost elements, which should be taken into account when evaluating the total costs of a MW- /RF-product:

- design costs
- material costs
- manufacturing costs
- costs spanning over the lifetime of the product

Many MW- /RF- applications include difficult geometries or materials regarding traditional manufacturing processes (e.g. turning, milling or casting). This means that much time is needed to develop the first prototypes to be suitable for production. The design costs of a microwave component can be estimated to be at least double compared to any "non-high-tech" product.

MW- /RF-devices utilize several precious and expensive materials. E.g. gold or silver or some specially mixed powders are needed. It is also usual that the quality grade of alloyed metals used in microwave applications is extremely good and the price therefore higher too. If expensive materials are used their price is essential. In addition to this some of these materials are difficult for traditional manufacturing processes or at least some special arrangements are needed during production. These double the effects of material selection to the price. A direct comparison between a MW- /RF-application and "non-high-tech" product is hard to make, but typically material costs is at least ten times higher. In this waveguide ring resonator construction these types of expensive materials is used in the SMA-connector. Usually small batches of the standardized SMA-connectors can be purchased with lower prices from suppliers than it is possible to produce by using own manufacturing process. In addition, possible requirements of lower losses lead to use of e.g. silver coating on the inner walls of the cavity of the resonator.

In general MW- /RF-applications need specialized tooling and fixing systems and in some applications, depending mostly of the operating frequency, quite tight dimensional tolerances down to 1 μm. These call for some extra time to make a dedicated set-up into the production system. Although the manufacturing stages themselves could be quite cost-effective, the long set-up times and specialized tools and fixings increase production costs by about 500 to 800 per cent in prototyping or small series production. In high volume production these cost elements are marginal. There is a tight relationship between manufacturing costs and surface roughness. After the specified surface roughness level the costs will increase exponentially. Nowadays in milling and turning the limit is 0.8 μm and in grinding 0.4 μm. A better surface finish rapidly adds costs. Many MW-/RF-applications tend to lead to over-estimated dimensional accuracies. The surface requirements may be set too tight to ensure the products performance though an easier way might have been e.g. to change more reliable connectors to the device. The most important thing is to compose the requirements of dimensional accuracy and surface finish from the operating frequency of the device. In this construction the required IT-grade is IT-6, which means that the critical allowed dimensional deviations are 6 – 19 μm and corresponding required R_a is 1.6 μm. The IT-6 grade is required to ensure ground-connect between the connectors and the resonator construction and characteristics of the fittings of the cover and the body. The losses of the designed resonator structure are minimal also with more rough surfaces. (see Figs. 5.5 – 5.7)

In MW-/ RF-device production the traditional principles to handle tooling costs, fixed costs, capital costs, labour costs, indirect labour costs etc. are as usual. The main acts should be focused in decreasing the lead-time that is to minimize the time required to start production.

In many cases also MW-/ RF-components should withstand environmental loads and there is a reason to compare different materials and their lifetimes. This comparison is typically made between two alternatives:

a) common base materials with an appropriate coating, a relatively short lifetime, the product must be changed due to a break-through in the coated surface, relatively cheap
b) specialized base materials, a long lifetime, no changes needed during the lifetime, extremely expensive

To make the comparison a ratio, which shows the price in the form of a "unit" like [performance/ price/ lifetime], is needed. Withstanding of environmental loading is not required for this resonator construction.

Regardless of technology - as long as the dimensional accuracy is met with a standardised process - the costs depend only on the manufacturing time. Immediately if there is a need to change the process to ensure a better accuracy or dimensional tolerances the price rises essentially. To manufacture this resonator construction standardised processes can be used.

The development process of many high-tech products normally includes several prototype phases and tests before the final design. Unfortunately these prototypes can constitute the largest portion of the total developing costs. To minimize the costs of a prototype several manufacturing technologies could be applied:

- the prototype could be made of some soft materials like foam or plastic by using simple milling or tuning operations
- the prototype could be manufactured by casting but the mould and the casting model are made of some cheap material
- scale models could be utilized
- rapid prototyping could be used (the geometry of the component is laser sintered according to the computer aided model)

One serious problem is that if the prototype is not manufactured with the final manufacturing technology, at least some of the geometrical limits are compromised. E.g. there are important rules for designing a product for casting or powder metallurgy, which are not necessary if the prototype is manufactured by using milling or tuning. In practice this means re-design for final manufacturing, which increases cost. Additionally, the surface quality or dimensional tolerances may have a weak basis if the prototyping scheme relies on a different technology. Based on the results of this research a prototype of the waveguide ring resonator construction will be manufactured. The manufacturing will be carried out by using simple milling and turning technology. Table 9.1 presents the most important cost factors for various groups of manufacturing technologies.

Table 9.1. Cost factors for various manufacturing technologies

Manufacturing technology	Most important cost factors
Forging processes	- tool and die costs related mostly to complexity of the workpiece
Extrusion and drawing processes	- tool and die costs related mostly to the selected process (e.g. hydrostatic extrusion needs special equipment)
Powder metallurgy	- die and model costs - manufacturing processes of the powder itself are expensive - finishing processes - quality checking
Casting	- die and model costs - finishing processes - quality checking
Machining	- set-up times - tooling and fixing systems - programming (tool control)

There are some derived ratios to estimate MW- /RF-component's total costs These characteristics are describing the effectiveness of production and the investment costs are taken into account as well. When utilizing these types of ratios the designer calculates e.g. the costs due to changes, which should be made to the product to improve the maximum gain with one single dB-unit. After that the design procedure continues by calculating the cost ratios for attenuation, noise, phase error etc. Arrows [↑ or ↓] after each unit describe whether the aim is to maximize or minimize the corresponding property. E.g. the designer is searching the minimum manufacturing accuracy (IT-grade), which still satisfies the performance requirements of allowed attenuation and noise but yet gives the desired gain level. After having collected all the ratios listed above the designer is able to make a numeric and objective comparison between various product alternatives. For this research topic the most important optimising ratios are as follows:

- costs [€] [↓] / attenuation [dB] [↓]
- costs [€] [↓] / phase error [rad] [↓]
- costs [€] [↓] / lifetime [h] [↑]
- costs [€] [↓] / frequency selectivity [MHz] [↑]
- accuracy of [IT-grade] [↓] / attenuation [dB] [↓], costs [€] [↓]

10 SUMMARY

In this research manufacturability analysis is made for an E-plane waveguide ring resonator. Possibilities to utilize concurrent engineering method both for designing and making manufacturability analysis for MW- and RF-components is discussed. For helping to establish the necessary guidelines for easy manufacturing and assembly of the waveguide ring resonator the specialised DFM(A)-questionnaire was generated.

Concurrent Engineering Design (CE Design) is noted to be an efficient design methodology and well suitable for the waveguide ring resonator structure design. The assembly of the waveguide ring resonator structure consist of three main components; the ring cavity, the cover and the SMA connectors. Manufacturability aspects, possibility of automated infrastructure support, economical aspects and microwave design aspects have been used in the design procedure at the same time. The mechanical 3D-modeling during the design process is used to ensure possibility of assembly of all parts and also to eliminate possible double-tolerancing of the cover and the cavity assembly. Additional requirements for the waveguide ring resonator from the market analysis can be also used to define properties of the ring cavity, SMA connectors and all the structure. If customers would like to use other connector types than SMA in the coaxial to the waveguide transitions, the properties of substitutive connector type could be taken into account and both advantages and disadvantages of the choice will be utilized in the design for manufacturing.

Based on the results gained during this research, Concurrent Engineering Design method will be recommended to be used for improving the microwave mechanics and components' design and manufacturing processes.

In the future, this research will be continued with the design of other types of waveguide ring resonator structures and also with other cavity resonators. An extensive comparison table of electrical properties of different aluminium alloys for RF-/MW-designers will be carried out by using data obtained during this and future research projects.

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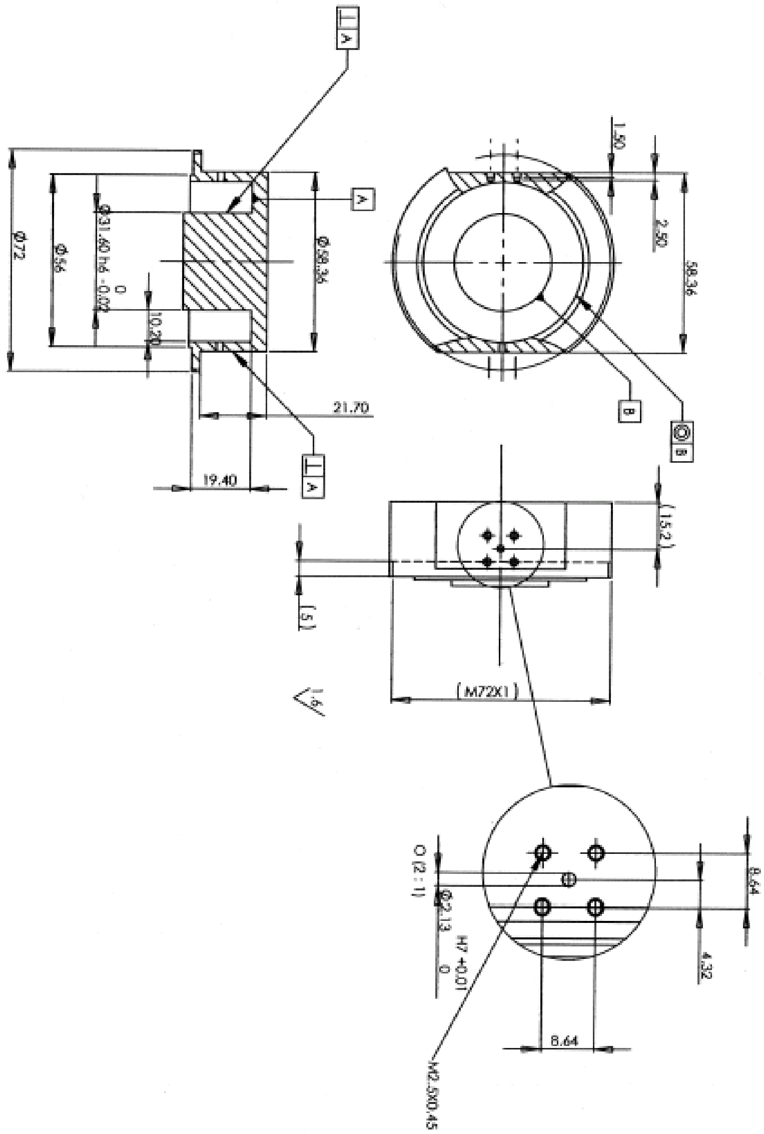
APPENDICES

Appendice 1: Dimensions of the body of the resonator.

Appendice 2: Dimensions of the cover of the resonator.

Appendice 1: Dimensions of the body of the resonator.



Appendice 2: Dimensions of the cover of the resonator.