DESIGN AND MANUFACTURING IMPROVEMENT OF A RESONATOR CAVITY FOR ULTRA-LOW PHASE NOISE OSCILLATORS

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Bachelor's Programme in Mechanical Engineering

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Examiner(s): Docent Tapio Saarelainen

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ABSTRACT

Lappeenranta–Lahti University of Technology LUT

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Mechanical Engineering

Double Degree, in co-operation with partner university: Hebei University of Technology

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Design and Manufacturing Improvement of a Resonator Cavity for Ultra-Low Phase Noise Oscillator

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50 pages, 25 figures, 4 tables and 3 appendices

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Keywords: resonator cavity; low phase noise; Q-factor; manufacturing

This paper focuses on the design and manufacturing optimization of ultra-low phase noise oscillator resonators for remote sensing satellites. These oscillators require high frequency stability, which directly depends on the Q value of the resonator. To address the challenges posed by extreme space environments, such as thermal fluctuations and radiation exposure, this study used a triangulation method, combining expert interviews, literature reviews, and DFMA analysis based on SolidWorks to perform multi-dimensional analysis.

Research explores material selection, geometric tolerances, and coating options to improve performance and manufacturability. The optimized design prioritizes high conductivity, low surface roughness, and mechanical stability under space conditions. Research results show that using 6061-T6 aluminium with silver and gold coatings can achieve a balance between electrical performance and structural reliability, thereby effectively increasing Q value and reducing phase noise.

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And a special thanks to my classmates and Dr. Harri Eskelinen for their discussion and feedback.

SYMBOLS AND ABBREVIATIONS

Roman characters

σ	Conductivity	[S/m]
μm	micrometre	[10-6 m]

Superscripts

$'$	stator
$''$	rotor

Abbreviations

CNC – Computer Numerical Control

DFMA – Design for Manufacturability and Assembly

EMI – Electromagnetic Interference

IT6 – International Tolerance Grade 6

RF – Radio Frequency

SMA – Sub Miniature version A (Connector type)

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1 Introduction

Remote Sensing Satellite is an important tool for humans to monitor all kinds of data on Earth. It is sent to space by a rocket to obtain information about the target area by emitting electromagnetic waves to the Earth's surface and receiving echo signals. Its uses include detecting physical properties of the Earth's surface, ocean, atmosphere, and outer space. The resonator cavity of an ultra-low phase noise oscillator is one of the important components of remote sensing satellites. An ultra-low phase noise oscillator is a high-stability frequency source. Its core function is to provide a stable, low-noise, high-purity sine wave signal. The resonator is one of the core components of an ultra-low phase noise oscillator. Its main function is to stabilize the frequency of the oscillator and ensure the high stability and low noise characteristics of the output signal. In remote sensing radar satellites, the stability and low loss characteristics of the resonator directly affect the signal quality of the oscillator, thereby affecting the detection accuracy of the radar system.

To achieve the best performance, phase noise must be minimized and the quality factor maximized. This is a complex design challenge, influenced by many factors, including material selection, thermal stability, and manufacturing accuracy. This paper will study this and study its manufacturability through DFM analysis of the resonator cavity.

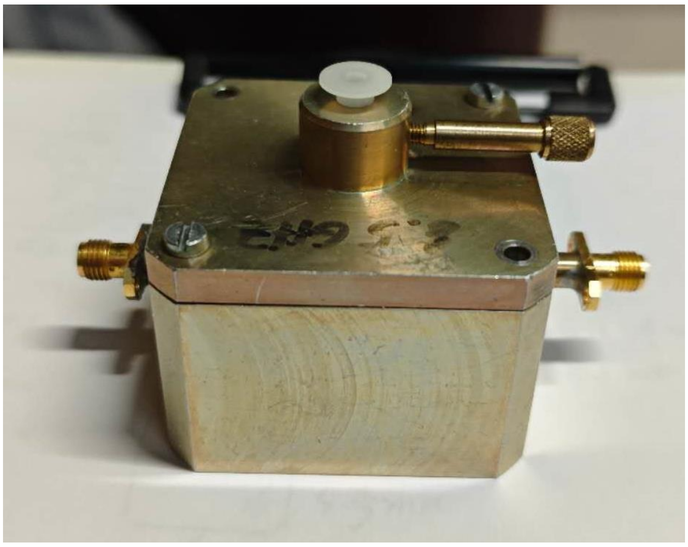


Figure 1. The main structure of the resonator cavity.

Figure 1 shows the resonator equipment provided by the school.

1.1 Goal of the research

The purpose of this study was to perform DFM analysis of the resonant cavity of ultra-low phase noise oscillators used in remote sensing radar satellites and optimize their manufacturability. The study focused on minimizing phase noise, maximizing the Q factor, and reducing temperature effects while ensuring mechanical accuracy and structural integrity in extreme spatial environments.

1.2 Background and motivation

The topic of this thesis belongs to the broader research project at LUT University during the year 2025. The research project focuses on the DFMA and sustainability analyses. The results of this thesis will be utilized later to build an overall picture of the DFMA and sustainability aspects related to MW and RF technology.

To achieve the best performance, the phase noise needs to be minimized, and the quality factor maximized. This presents a complex design challenge that is affected by multiple factors, including material selection, thermal stability, and manufacturing precision.

The mechanical design of the resonator cavity must consider the extreme space environment, where periodic temperature changes and cosmic radiation exposure can degrade performance. Material selection is a key consideration because of the different thermal expansion coefficients between components such as the dielectric disk, glass positioning rods, and aluminium housing. If not carefully handled, these variations can compromise frequency stability.

1.3 Research problem and research question

When studying this machine, it is important to combine the performance requirements of the resonator chamber with factors such as the characteristics of the material and the accuracy required for geometry. For precision devices such as resonators, proper use of case sizes and geometric tolerances is critical to ensure proper assembly conditions. The most important challenge to be addressed is the harsh environmental conditions in space. The space environment has factors such as extreme temperatures and radiation. This will influence material selection and proper manufacturing, particularly in connection and coating technology.

By analysing the research problem, the device faced a series of questions:

Which manufacturing method is suitable for the manufacturing needs of resonator shell geometry? How to ensure the quality of gold plating? On what basis?

How do the material selection and geometric design of the resonator cavity affect its thermal stability?

How to address the long-term impact of space environment on the performance of the resonator cavity?

1.4 Research methodology

This study employs a triangulation methodology consisting of:

Expert Interviews – Gathering insights from professionals in RF systems, satellite manufacturing, and materials science to guide design decisions.

Literature Review – Evaluating existing research on resonator cavity materials, phase noise reduction, and structural performance in space environments.

SolidWorks-Based Simulation and DFMA Analysis – Modelling and simulating the resonator cavity to validate design feasibility, thermal stability, and mechanical resilience.

By combining these approaches, the research ensures a balanced integration of theoretical, experimental, and industry-based insights.

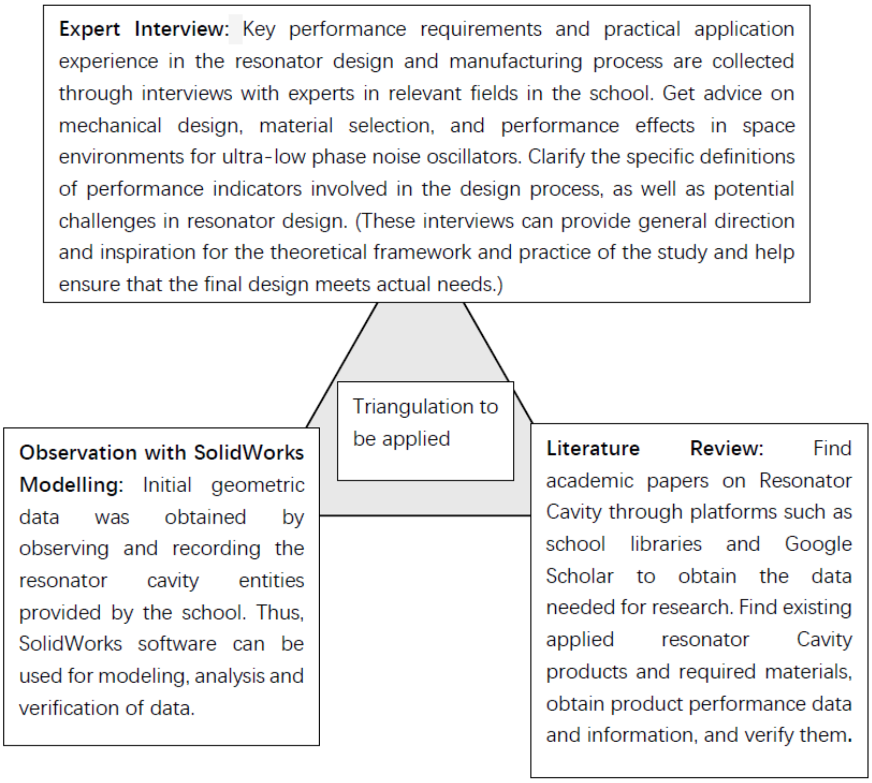


Figure 2. The triangulation’s chart

Figure 2 visualizes the three analytical methods of triangulation and its application.

1.5 Expected contribution

The expected contributions of this study include:

A validated resonator cavity design that improves Q-factor, minimizes phase noise, and ensures long-term thermal stability.

Optimize material selection and select materials that can maintain good thermal stability and mechanical elasticity in a space environment.

Design for Manufacturability (DFM) principles to enhance precision and efficiency in manufacturing.

A methodological contribution using triangulation research for future RF device optimizations.

2 Method

The research method for developing the manufacturing plan of the frequency converter in deep space probe of this analysis is based on triangulation method. Triangulation is a technique for analysing the same research results using different data collection methods. It is used for three main purposes: improving effectiveness, creating a more in-depth picture of the research problem, and asking about different ways to understand research questions. (Nightingale, Andrea J. 2019) The application of this method is reflected in cross-verifying research results through various methods such as expert Interviews, literature review, and the use of professional software analysis to reduce bias and improve the reliability and effectiveness of the research. In my research, the analysis software used was SolidWorks and the DFMXpress plug-in that comes with SolidWorks. This chapter describes in detail how to apply this method to resonator research, as well as the specific process and details of its application.

2.1 Applied triangulation

In order to improve the overall reliability and theoretical depth of the study, this study uses the triangulation method (Triangulation Method) as the core research framework. Through a combination of diverse information sources and analytical perspectives, the design and manufacturing process of the resonator chamber was systematically evaluated. As a multi-method mutual verification research strategy, triangulation is widely applicable in engineering design and manufacturing optimization research, and is particularly suitable for exploring this topic in multiple dimensions such as technology, process, and reliability.

The triangulation method in this study consists of the following three core pillars: Expert Intervie, which is used to obtain first-hand industry experience and actual manufacturing considerations, and can refine key manufacturing bottlenecks and spatial environment factors. Literature Review. Literature reviews are used to establish theoretical foundations, identify industry standards, and existing research results. Theoretical bases such as material selection, Q-factor optimization, and coating requirements can be established. SolidWorks DFMA analysis, which is numerically verified for the manufacturability and tolerance analysis of structural designs, can provide structural optimization suggestions, complex component ratings, and assembly rationality suggestions.

The application of triangulation is carried out through several stages of this study, including: problem definition stage, determining research priorities through literature and expert opinions; model design stage, combining SolidWorks simulation with literature parameters to verify modeling rationality; and results analysis stage, where DFMA analysis results are cross-compared with expert opinions and theoretical data to evaluate the reliability of the findings.

The triangulation method in this study played a key role, such as enhancing the credibility of conclusions, confirming each other from multiple sources of information, and improving research persuasiveness;Identify potential conflicts, and when expert opinions deviate from simulation results, further analysis of the reasons behind them; fill gaps in information: some design details not mentioned in the literature can be added by experts, and vice versa; improve structural integrity: the method itself forms a “multiple guarantee” mechanism, making the research more systematic and complete.

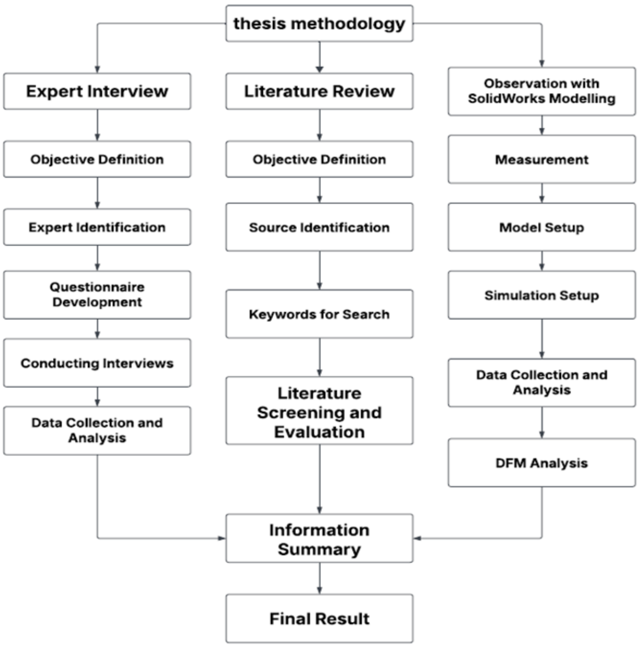


Figure 3: Flowchart to applied triangulation

Figure 3 shows the application and application process of triangulation. In short, by introducing a triangulation system into this study, the researchers not only achieved full process coverage from theory to practice, but also provided reusable research structure templates for manufacturing topics, which is conducive to improving the reliability and stability of the research.

2.2 Arrangements for expert interview

1. The Objective: The purpose of the expert interviews is to gather opinions from senior professionals in fields related to the resonators being studied, such as RF system design, materials science, and satellite engineering. Advice and data obtained from professionals can help conduct research and provide inspiration for research in search of research directions. This approach ensures the incorporation of practical perspectives, complements theoretical findings, and validates key hypotheses in the study.

2. Objective Definition: Before the interview, it is necessary to collect basic data about the study and determine the research goals. Through keyword searches and literature searches in school libraries, a preliminary understanding of the remote sensing satellite ultra-low phase noise oscillator resonator was formed, and the research goals were initially clarified.

3. Expert Identification: At this stage, the main task is to determine the number and selection of experts to be interviewed. The suggestions and opinions of experts with more extensive work experience and larger expert groups are more indicative than the results after comparison. I would like to thank LUT University for their support, which provided me with the opportunity to interview a professor in the field of electrical and automation at Aalto University. Professor Pekka has extensive experience in designing, testing, and manufacturing various types of MW and RF components. I have an in-depth understanding of the RF component where the resonator studied in this article is located. The interaction with Professor Pekka will provide a solid information foundation for this study to analyze the design and manufacturing optimization of ultra-low phase noise oscillator resonators in remote sensing satellites.

4. Questionnaire Development: The opportunity for expert meetings is invaluable. To ensure the smooth running of the conference, that is, to obtain accurate information from experts and not waste time between the two parties, it is necessary to draw up an outline of topics in advance. After identifying the experts to be interviewed, the researchers drew up an outline of the conference in advance based on the information to be confirmed during the conference.

The conference syllabus ensures that conversations are focused on core topics and that more accurate information is obtained from experts. So, I prepared a list of questions before the meeting.

First question: In resonator cavity design, which structural factors are most critical to increasing the Q value? Second question: What are commonly used resonator materials? Third question: What are the special requirements for material selection in RF equipment applications? Fourth question: In resonator manufacturing, which process steps have the greatest impact on the final Q value? Fifth question: How does long term temperature cycling change the resonator's performance?

The resonator studied in this paper is an important element in remote sensing radar satellites and faces the need to work in extreme environments in space. Therefore, to obtain accurate information from experts and not waste time between the two parties, the question I asked the experts during the conversation focused on: In the space environment, what factors affect the resonator's ultra-low phase noise oscillator's resonator performance?

5. Conducting Interviews: The interview time with the experts will be according to the schedule set by the school, and this expert meeting is scheduled in the early stages of writing the paper. The conference was held online, I have 10 minutes to interact with experts. With the expert's agreement, the meeting will be recorded to facilitate analysis.

6. Data Collection and Analysis: After the interview, the researchers will conduct a thematic analysis based on the minutes of the conference to determine the answers to each research question, missed research questions, and expert opinions on other research topics. Based on this information, the researchers began preparing the first edition of the report. The completion of the paper requires repeated verification. Once the first edition of the report is completed, it will be submitted to the professor, who will provide comments on the first edition of the report, pointing out shortcomings or areas that still need to be explored in the analysis.

The researchers will revise the first edition of the report based on the professor's comments, fill in the gaps, and then invite the professor to review it again. Through multiple rounds of feedback, the analysis content was continuously revised and improved, and a final report was finally formed, and consensus was reached with experts.

7. Expected Outcomes: The researchers found a solution to the initially established research problem. By comparing expert opinions and literature, there is a systematic research direction on the design and manufacture of ultra-low phase noise oscillator resonators in remote sensing satellites.

2.3 Flowchart presentation of literature search and review

1. Objective: The literature review lays a theoretical foundation by analyzing existing research on resonators, material properties, and space environment conditions, summarizing data used to study the design and manufacturing optimization of ultra-low phase noise oscillator resonators in remote sensing satellites, research gaps and industry benchmarks. It also identifies gaps in current research to guide experimental validation.

2. Objective Definition: The main purpose of the literature review is to study the design of ultra-low phase noise oscillator resonators for remote sensing satellites and conduct manufacturability analysis. This includes exploring the integration of advanced materials, precision device manufacturing processes, and space environment research.

3. Source Identification: To ensure the reliability and relevance of the literature, researchers use specific databases and criteria for source selection:

Databases: Outside of the school's database, researchers will use IEEE Xplore, LUT Primo and Scopus were utilized to access peer-reviewed journals, conference proceedings, and technical reports. These platforms provide high-quality resources in the domains of RF engineering, materials science, and environmental engineering.

Exclusion criteria: Sources are assessed based on metrics such as SJR score of journal influence and SNIP (influence of source standardization for each paper) of field correlation. Prioritize articles published within the past 10 years to ensure researchers are getting the latest insights and avoiding outdated information.

4. Keywords for Search: By properly selecting keywords and using multiple relevant keyword combinations, it is possible to quickly locate literature highly relevant to the research topic without browsing a large amount of unrelated content.

The literature search was conducted using specific keywords to target relevant studies, including:

•"Resonator cavity optimization"

•"Ultra-low phase noise oscillators"

•"Space-grade materials"

•"Sustainable manufacturing in RF systems"

•"Circular economy in electronics"

Questions Q1-Qn, to which the answers are searched for	Reference #1	Reference #2	Reference #3	Reference #4	Reference #5	Reference #6	Reference #7	Reference #8	Reference #9…	Reference #N	Summarized observations to integrate the final answers to each question
Q1：What unusual requirements do space conditions place on DFM for components of resonators used in ultra-low phase noise oscillators?			√	√	√						Equipment needs to withstand extreme temperature changes and the long-term effects of cosmic rays. DFM design must consider differences in mechanical vibration and thermal expansion, select materials with low vibration sensitivity, and significantly reduce the impact of mechanical vibration on phase noise through mechanical damping and active damping techniques.
Q2：What are the main challenges in maintaining mechanical stability and dimensional tolerances of resonators in extreme space environments?				√	√	√				√	Key challenges include: Mechanical vibration and shock (frequency can be fine-tuned using tuning screws [5].) Temperature changes (using materials with a low coefficient of thermal expansion [3]) Dimensional tolerance control (use of aluminum housings (Ref. [10]) and fiberglass positioners [4] to achieve fine tolerance control of mechanical components)
Q3：How does the choice of coating material affect performance?	√		√		√						Highly conductive coatings, such as silver plating, can significantly reduce surface resistance and increase the Q factor. Appropriate coating materials can maximize the reflectivity of electromagnetic waves and reduce power loss. [3] In space applications, gold plating also provides protection against corrosion and cosmic rays to ensure stable long-term performance.
Q4：How to quantify the Q-factor value of RF components such as resonators?	√	√				√	√	√	√	√	1. The unloaded Q factor (QU) is calculated from insertion loss (IL) and resonance frequency (f). 2. Using microwave reflectometer (microwave reflectometer) and resonance spectrum analysis methods, the Q factor was accurately calculated by measuring the S parameter (S11) and fitting the phase slope.
Q5：How do the material selection and geometric design of the resonator affect its thermal stability?	√	√	√	√		√	√		√	√	In design, priority should be given to materials with low thermal expansion coefficients and multi-layer structures, plus designs such as tuning screws and silver plating on harmonic chambers to achieve coordination of thermal expansion and minimize stress effects.
Qn											
Summarized observations about the relevance of each reference	The effects of coating material selection on conductivity and surface smoothness are provided, and the definition and measurement methods of the Q factor are explained in detail.	Through the method of optimizing the Q factor, the effects of material selection and surface treatment on improving the thermal stability and Q factor of the resonator were demonstrated.	The excellent electromagnetic properties of polycrystalline diamond in high frequency and low temperature environments have been studied, and its advantages in improving the thermal stability and conductivity of resonators have been proven.	Methods for designing and manufacturing microwave components under spatial conditions are provided, and the system explains the effects of mechanical stability, material selection, and coating technology on performance.	A method for achieving mechanical stability by tuning screws is provided, and how to optimize the phase noise performance of a resonator by quantifying the Q factor is shown.	Through electromagnetic coupling design, methods for improving the Q factor and achieving ultra-low phase noise are shown, which is suitable for resonator design in space applications.	The vibration sensitivity of microwave components has been studied, and specific methods for maintaining mechanical stability in a space environment, particularly in terms of vibration suppression, have been proposed.	The effects of calibrated and uncalibrated methods on the accuracy of the Q factor measurement were compared, and a reliability analysis of the experimental methods was provided.	An experimental method for measuring the Q factor using a microwave reflectometer is proposed, especially for application in composite acoustic resonators, which supports multi-frequency applications.	The phase noise performance of SAW resonators was studied, and mechanical stability under extreme temperature conditions and the effectiveness of achieving ultra-low phase noise through carrier suppression technology were verified.	

Figure 4. Source materials analysis tool

Figure 4 shows how to use the Source Analysis Tool to search for suitable literature.

5. Literature Screening and Evaluation: After an initial search, the selected articles are strictly screened for their relevance and quality. Studies that focus on outdated technology or lack peer review were excluded. Special attention is paid to research exploration:

The relationship between material properties, such as dielectric constant, thermal conductivity and resonator performance.

The impact of extreme environmental conditions, such as temperature fluctuations and radiation, on equipment reliability.

A comparison of manufacturing technologies, such as CNC machining and additive manufacturing, in terms of accuracy, sustainability, and scalability.

6. Expected Outcomes: Applied triangulation The literature review provides a robust foundation for this study, offering insights into the optimal material selection and design strategies for resonator cavities. Through a selection of literature, important insights are provided on the theory and practice of resonator design, material properties, and environmental challenges. Solve pre-set research questions. Finally, in the report, the researchers were able to ask questions about material properties and performance, environmental challenges in space, design optimization strategies and research gaps and future directions.

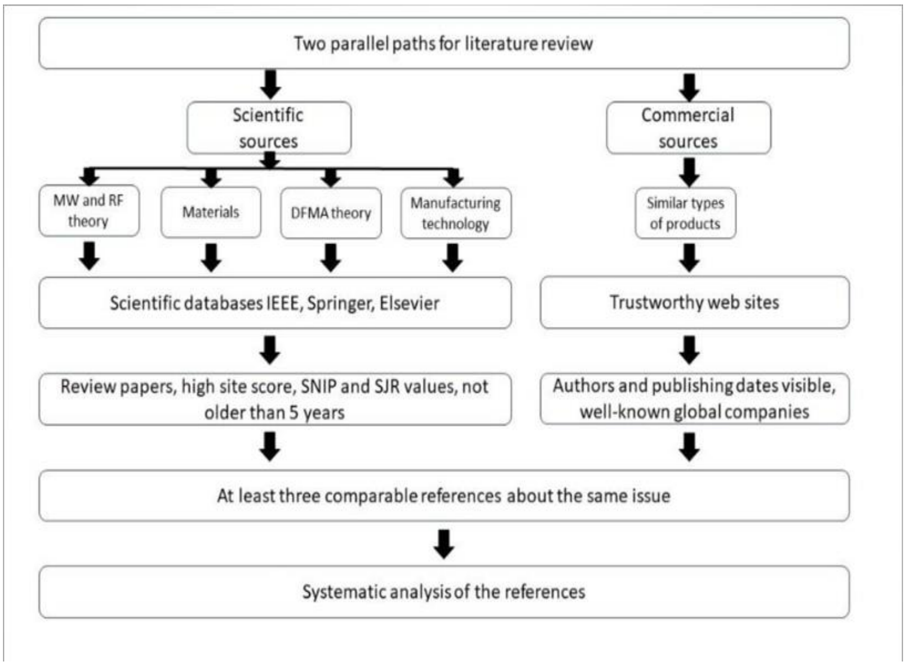


Figure 5. Flowchart presentation of literature search and review.

Figure 5 shows the application process of the literature review method.

2.4 Utilization of SolidWorks DFMA Modul

To study the mechanical design requirements of the resonant cavity and ensure that the design can be both manufactured and assembled, this study integrated SolidWorks DFMA (Design for Manufacturability and Assembly). The goal of SolidWorks modeling is to ensure the structural integrity and geometric tolerances of all components and conduct manufacturability analysis. The resonant cavity is a precision RF component, and slight differences will affect its phase noise.

SolidWorks DFMA Analysis:

Step 1: Create 3D parametric model of the resonator cavity.

The LUT provides the researcher with a resonant cavity entity, and the study requires accurate measurement of the entire device. The resonant cavity contains the resonant cavity body, cover, tuning screw, PTFE busher, two SMA connectors, and four screws. The measurement process includes measuring the length, width, and height of the device outside the resonant cavity, as well as measuring the depth, width, and length of the cavity. In addition, the location of each hole on the device also needs to be accurately located. Based on the resonant cavity entity, the surface processing technology and production process of the components can also be inferred. Except for the inner surface of the resonant cavity, which is silver-plated, the surfaces of other original parts are gold-plated.

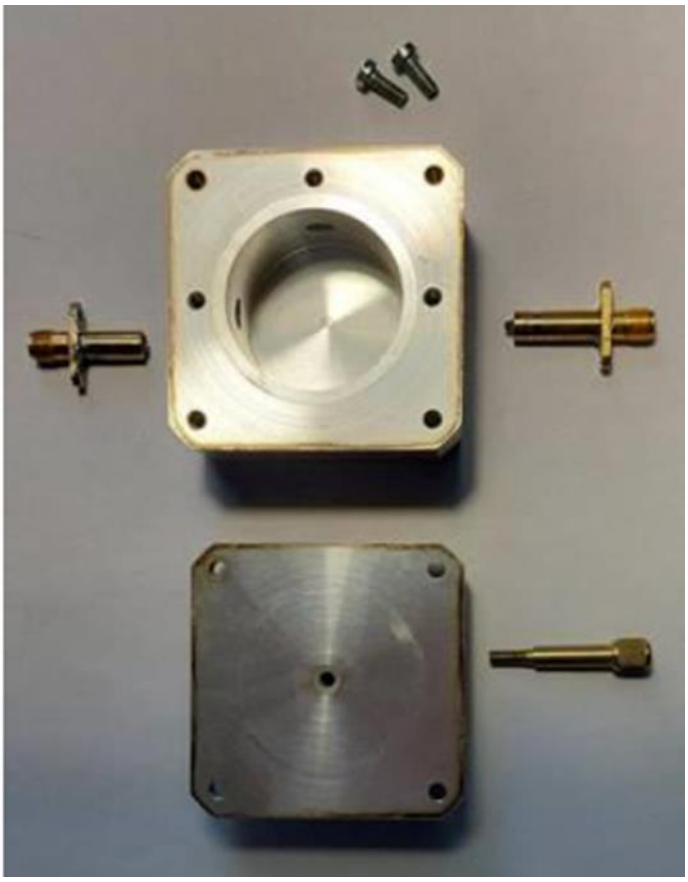


Figure 6. The mechanical structure of the device

Figure 6 shows the components and structure of the equipment.

Step 2: Perform dimensional tolerance analysis for machining precision.

In the process of manufacturing mechanical parts, tolerance is very important and affects the expected function, form and manufacturing process of the components. When making the model drawings, the researchers fully considered the geometric tolerance, surface roughness and other characteristics of the equipment to ensure the processing accuracy. Among all the components, the two SMA connectors are standardized components, and their models and data sheets are obtained from Amphenol. A steel pipe is welded to adapt to the needs of the resonant cavity.

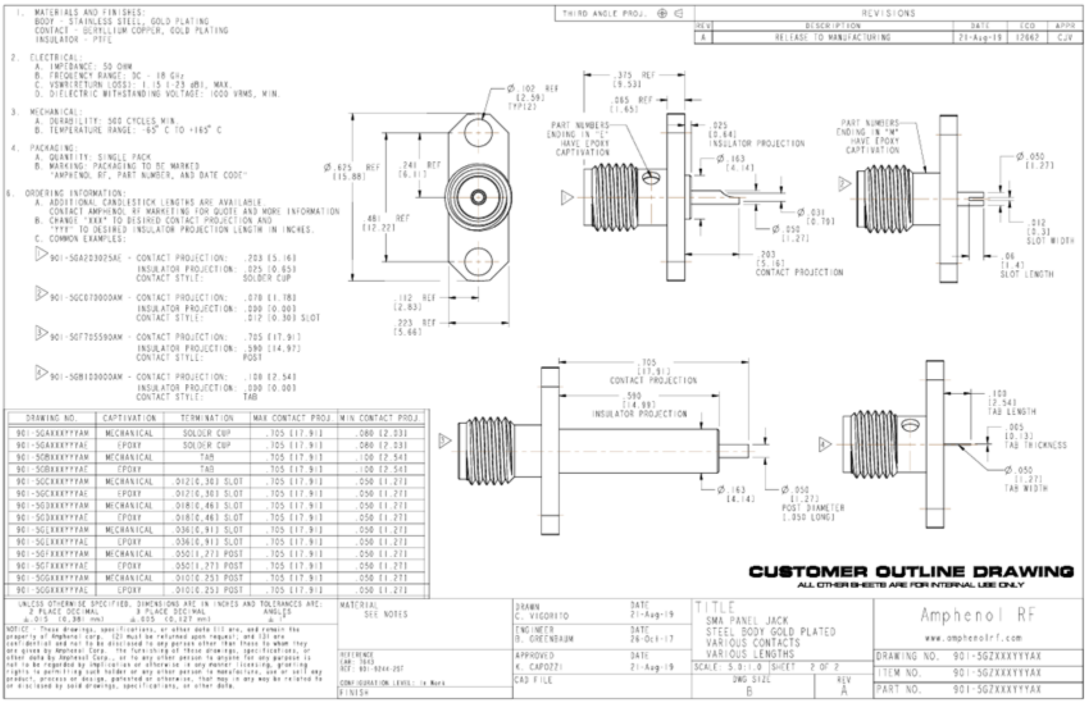


Figure 7. Datasheet of SMA

Figure 7 shows a drawing of a standardized SMA connector.

Step 3: Use DFMA to determine the design modifications.

For the DFMA tool, the study selected the DFMXpress tool that comes with SolidWorks. DFMA analysis is performed on all components of the resonant cavity. Through the DFMA results, the manufacturability and optimizable points of each component can be analysed. Assisted by other data analysis, the design and manufacturability of the resonant cavity can be optimized.

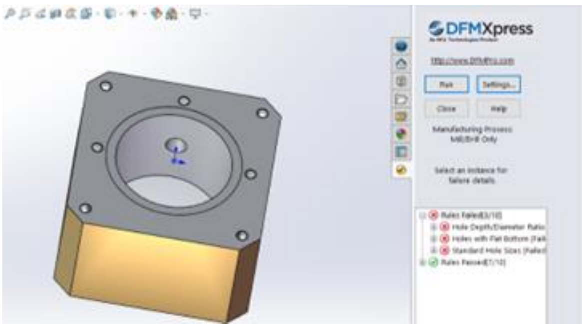


Figure 8. DFMXpress

Figure 8 shows DFMXpress's DFMA analysis of the resonator body.

2.5 Means to carry out reliability analysis

Reliability analysis ensures the accuracy and consistency of study results. In this study, reliability was achieved through triangulation, which combined insights from multiple sources to reduce bias and enhance the validity of conclusions. By integrating expert interviews, literature reviews, and SolidWorks simulations, this approach creates a comprehensive verification framework for optimizing resonator design and performance under space conditions.

The triangulation method follows three main verification steps: Expert interviews: Providing industry-based insights, practical considerations, and empirical verification. Literature review: Ensure consistency with established theory and scientific research on resonator optimization. SolidWorks DFMA simulation: Provides numerical and engineering-based verification of manufacturability, mechanical stability, and performance indicators.

To improve reliability, results from different sources were cross validated:

1. Comparing expert opinions with literature, experts believe that surface roughness has a significant impact on the Q factor and phase noise. This was confirmed by a literature review, citing experimental studies showing a correlation between surface quality and signal loss.

2. Using simulated data to verify expert insights, experts emphasized the impact of material selection on frequency stability. SolidWorks needed to simulate different materials through analysis to prove that aluminium alloy achieved a balance between manufacturability and thermal stability.

3. To ensure that the literature results are consistent with the analogy data, resonator coating studies have highlighted the advantages of silver plating in minimizing resistance loss. The 3D model analysed and simulated different coating thicknesses to verify that the best coating can improve electrical conductivity without excessive manufacturing complexity.

When discrepancies occur, additional verification steps are required: Experimental testing suggestion: If the simulation data conflicts with the literature, try empirical testing of the prototype components. By integrating multiple verification sources, the reliability of resonator manufacturing recommendations has been improved. Balance theoretical predictions with real-world engineering constraints. This is how we find a structured, evidence-based approach to minimize phase noise and maximize the Q factor in spatial applications.

This structured triangulation framework ensures that research results are both scientifically rigorous and practical, thereby improving the reliability and applicability of research findings.

To ensure that the trigonometry framework can be intuitively expressed to ensure that the research results are scientific and practical, the study used the following tabular tools to systematically analyse the reliability of trigonometry. The final analysis results will be presented later.

Method in the triangulation	Validity	Reliablity	Sensitivity	Mathematical error analysis	Accurac y	Saturation
Method #1						
Method #2						
Method #3						
Triangulatiuon itself						

Figure 9. Reliability analysis table

Figure 9 shows an analysis tool for the reliability of the method applied to the paper.

3 Result and Analysis

This section shows the results obtained by three research methods based on trigonometry. Includes a summary of the expert talks; data analysis based on a literature review; and DFMA analysis using SolidWorks.

Based on the three methods, the study returns the results of analysis of material selection, coating selection, processing problems, and processing processes.

3.1 Literature review results

The literature review focuses on understanding the design, material selection, and performance requirements of resonators used in ultra-low phase noise oscillators in remote sensing radar satellites; and collecting and analysing relevant data.

Based on the problems to be solved in the research, the retrieved literature focuses on Q values, material selection, processing requirements, etc. This section will be described in six sections.

3.1.1 Resonator Cavity Design and Performance Factors

The main function of a resonator in a microwave oscillator is to maintain frequency stability and minimize phase noise. To this end, the key to design is how to maximize the device's quality factor (Q-factor), as it directly affects the phase noise characteristics of the oscillator. Multiple papers have mentioned that the Q factor quantifies the resonator's ability to store energy with minimal loss. A high Q factor indicates low energy loss per cycle, which is critical for applications requiring resonators. (Bogdanov, A. A. et al. 2019)

The **Q-factor (Q)** of a resonator is defined as the ratio of **stored energy** to the **energy dissipated per cycle**. Mathematically:

$$Q = 2\pi \times \frac{\text{Energy Stored}}{\text{Energy Lost per Cycle}}$$

Alternatively, in terms of **resonant frequency** f_0 and **bandwidth** Δf:

$$Q = \frac{f_0}{\Delta f}$$

Figure 10. Definition of Q-factor

Figure 10 shows the formula for defining the Q factor.

When designing, the study needs to consider factors such as geometric tolerances, conductivity, dielectric loss, thermal expansion coefficient, and surface roughness of the equipment. However, the working environment of the resonator chamber is an extreme environment in the universe, and drastic changes in temperature, radiation, etc. will bring many challenges to equipment design. Resonators are prone to failure and drift when exposed to extreme temperature fluctuations. This requires complex encapsulation and shielding to protect the components. Shankar, A. et al. 2014) (Sariri, K. 2006) Therefore, when designing, it is necessary to consider the differences in thermal expansion of the dielectric plate, its glass positioning rod, and the aluminum body of the equipment under extreme space conditions to stabilize the operating frequency range.

3.1.2 Mechanical Stability and Environmental Considerations

As an important component of remote sensing radar satellites, resonators must operate reliably under extreme space conditions, where factors such as mechanical vibration, thermal circulation, cosmic radiation, and vacuum conditions significantly affect performance. Therefore, ensuring mechanical stability and environmental resistance is essential for resonators used in ultra-low phase noise oscillators for remote sensing radar satellites.

For resonators, to ensure the stability of the output signal and low noise characteristics, the internal dielectric resonator elements in the cavity must maintain mechanical stability to prevent frequency drift. Random amplitude fluctuations are mixed into the oscillator's phase noise, causing frequency instability. (Qiao, Y. et al. 2022) Because it was discovered in Hati et al. (Hati, A. et al. 2007) that mechanical vibration affects phase noise; even small displacements of resonator elements can cause unwanted frequency fluctuations.

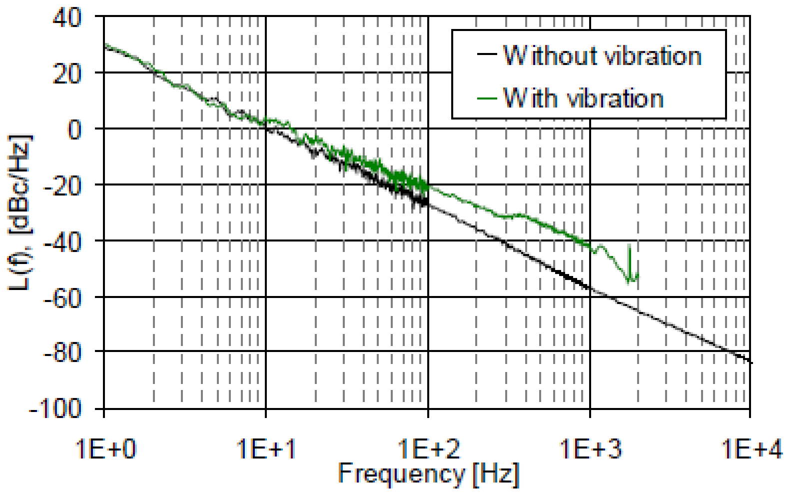


Figure 11. PM noise of the DRO with and without vibration along the z-axis. A random vibration profile of acceleration PSD 0.5 mgrms2/Hz for offset frequencies 10 Hz to 1500 Hz was used. (Hati, A. et al. 2007)

It can be seen from this that the design of the resonator cavity should minimize vibration sensitivity, and the design requires structural reinforcement and material optimization. In this regard, precision milling should be selected for the processing process of the resonator cavity, and the components are closely matched to reduce the impact of mechanical vibration. Furthermore, sapphire rather than metal is used as the material for the dielectric plate of the resonator, reducing frequency shift caused by mechanical stress while providing excellent dielectric properties. The space environment exposes components to extreme temperature changes. Spacecraft materials experience extreme temperature changes, usually between -175°C and 160°C. These cycles cause mechanical stress due to expansion and contraction, leading to material degradation. (YANG, J. C. & DE GROH, K. K. 2010) Drastic changes in temperature can cause the material to expand and contract, which can alter cavity size and reduce performance. Therefore, when selecting materials for resonators, materials with low thermal expansion should be used to prevent equipment deformation.

3.1.3 Material Selection for Resonator Cavity

Based on the question: How do you select the material of the resonator to improve its thermal stability? Combined with the previous analysis, resonator materials need to consider conductivity, dielectric loss, and thermal expansion coefficient.

	Relative Conductivity	Relative Permeability
Material	σ_r	μ_r
Aluminum (soft)	0.61	1
Aluminum (hard)	0.4	1
Copper	1.00	1
Steel	0.02	500
μ-metal	0.10	1,000

Figure 12. Typical Electrical Parameters for Some Common Construction Metals (Eskelinen, H. & Eskelinen, P. 2003)

Metal	Relative Conductivity in 20°C	Temperature Coefficient of Resistivity 1/°C
Aluminum (2S; pure)	59	0.0039
Aluminum (alloys):		
Soft-annealed	45–50	—
Heat-treated	30–45	—
Brass	28	0.002–0.007
Copper:		
Hard drawn	89.5	0.00382
Annealed	100	0.00393
Gold	65	0.0034
Iron:		
Cast	2–12	—
Nickel	12–16	0.006
Nickel silver (18%)	5.3	0.00014
Phosphor bronze	36	0.0018
Silver	106	0.0038
Steel	3–15	0.004–0.005
Tin	13	0.0042

Figure 13. Conductivity of Various Metals Subject to Variation According to Processing and Alloy Composition (Eskelinen, H. & Eskelinen, P. 2003)

Material	Thermal Expansion Coefficient ($\times 10^{-6}$ K^{-1})	Thermal Conductivity (W•m^{-1}•K^{-1})
Silver (Ag)	18.9	429
Copper (Cu)	16.5	401
Gold (Au)	14.2	318
Aluminum (Al)	23.1	237
Iron (Fe)	11.8	80
Nickel (Ni)	13.4	90.9
Titanium (Ti)	8.6	21.9
Zinc (Zn)	30.2	116
Tin (Sn)	22	66
Lead (Pb)	28.9	35.3
Galinstan (Gallium-Indium-Tin Alloy)	16.5	16.5

Figure 14. Thermal expansion coefficient and thermal conductivity of common metal materials

The above table provides information on the conductivity and thermal expansion coefficient of some common metal materials. Furthermore, material properties can be obtained from the SolidWorks material library.

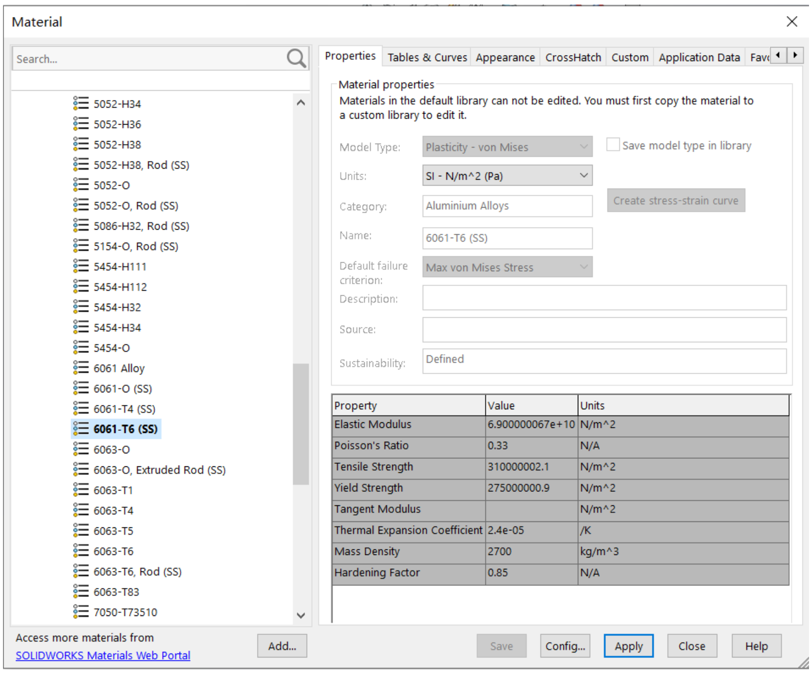


Figure 15. SolidWorks material library

To ensure the optimal balance between performance, manufacturability, and long-term reliability in space environments, a structured value analysis was conducted on candidate materials for the resonator cavity. This analysis considers key evaluation dimensions including thermal conductivity, machinability, electrical performance, surface finish potential, radiation resistance, and cost level.

Option / Factor	Thermal Conductivity (W/m·K)	Surface Finish Potential	Machinability	Radiation Resistance	Cost Level (€)	Overall Value
Aluminum 6061-T6	167	Medium (Ra 3.2–6.3 µm)	Excellent	Moderate	€	High
Copper (Pure)	390	Good (Ra ≤ 1.6 µm)	Difficult	Low	€€	Medium
Gold Plating (Ext.)	—	Excellent	—	Excellent	€€€	High
Silver Plating (Int.)	—	Excellent	—	Moderate	€€	High
Stainless Steel (Screws)	16	Poor (Ra > 6.3 µm)	Good	Excellent	€	Medium
PTFE (Bushing)	~0.25	N/A	Difficult	Excellent	€	Medium

Table 1. Value Analysis of Material and Manufacturing Options for the Resonator Cavity

To support decision-making with a more quantitative approach, the R9 weighted scoring method was applied. Each material was evaluated against six weighted criteria, scored on a 0–9 scale, with higher values indicating better performance. The weight percentages were assigned based on their relative importance in achieving high Q-factor, thermal stability, and manufacturability in a space environment. The resulting scores are shown in Table.

Dimension	Weight (%)	Aluminium 6061-T6	Copper (Pure)	Stainless Steel
Thermal Conductivity	20%	5 × 0.2 = 1.0	9 × 0.2 = 1.8	3 × 0.2 = 0.6
Machinability	20%	9 × 0.2 = 1.8	4 × 0.2 = 0.8	6 × 0.2 = 1.2
Conductivity	20%	5 × 0.2 = 1.0	9 × 0.2 = 1.8	3 × 0.2 = 0.6
Surface Finish Potential	15%	7 × 0.15 = 1.05	8 × 0.15 = 1.2	4 × 0.15 = 0.6
Radiation Resistance	15%	6 × 0.15 = 0.9	4 × 0.15 = 0.6	9 × 0.15 = 1.35
Cost	10%	9 × 0.1 = 0.9	4 × 0.1 = 0.4	6 × 0.1 = 0.6
Total Score	100%	6.65	6.6	4.95

Table 2. R9 Weighted Value Analysis for Resonator Material Options

The materials for all components of the resonator chamber are as follows (The materials are all from the SolidWorks material library):

Resonator chamber body and cover: 6061-T6 (SS)

Tuning screw: Commercial Bronze, UNS C22000 (90-10 Bronze)

PTFE busher: PTFE (general)

SMA Connectors: Screws: Body - stainless steel, contacts - beryllium copper, insulator – PTFE

Screws: Stainless steel

Dielectric disk: made of amorphous Zr–Sn–Ti-oxide stabilized at 600 °C (Amorphous Zr-Sn-Ti oxide is stable at high temperatures. Amorphous states are essential to maintain uniformity and prevent crystallization, which can cause crystal boundaries and high leakage currents. (Woods, K. N. et al. 2017)

3.1.4 Coating Materials and Surface Quality

The influence of materials on resonator performance was mentioned earlier. The question that ensues is: How does the choice of coating material improve performance? As an important processing process for mechanical components, how will the material and quality of the coating affect the performance of the resonator cavity?

As can be seen from research literature, material selection and surface quality of coatings play a key role in the performance of resonators in ultra-low phase noise oscillators. Properties such as conductivity, surface roughness, radiation resistance, and long-term stability of coating materials are critical to ensure high Q factors and minimal phase noise in radar and communication systems. (Guo, C. et al. 2024)

Choosing the right coating material can improve the conductivity of the component. A high-quality coating affects the rough surface of the component. In “Low Phase Noise Cavity Oscillator,” Maree explores how cylindrical cavity oscillators can achieve optimal performance by using silver coating and precision machining techniques to reduce surface roughness. (Maree, J. et al. 2013) Additionally, the coating protects components and optimizes thermal stability. In the case of the studied resonator, the coating on the inside of the cavity was silver coated, and the other components and the outer surface of the chamber were all gold coated. Both gold and silver have extremely high conductivity, which can greatly reduce component resistance loss and increase Q-factor. The smooth silver coating ensures that electromagnetic waves can travel effectively within the resonator chamber. The outer surface, connectors, and structural components are gold-plated because gold has strong oxidation and corrosion resistance, and can protect components exposed to atomic oxygen, cosmic radiation, and temperature changes. Additionally, special arrangements need to be considered to ensure that the coating in the screw holes is also of high quality. Advanced coating techniques such as electroplating, thermal spray, or chemical vapor deposition help achieve uniform coverage in complex geometric shapes such as screw holes. (Hyie, K. M. et al. 2022)

Plating Material	Plating Type	Application Area
Gold	Cyanide based, neutral pH, arsenic additive Cyanide based, immersion Sulphite gold Cyanide based, cobalt brightened	Generally in microwave mechanics Printed circuit boards Thin film circuits Connectors
Silver	Cyanide based, organically brightened Cyanide based, Selenium brightened	Microwave boxes Generally in microwave mechanics, connectors
Palladium	Nonammonium, Nonchloride Nitride based	Connectors General electronics
Copper	Acid based Cyanide based, bright	Connectors General electronic components and aluminum boxes
Tin lead	Bright	Connectors
Tin copper		
Nickel	Sulphate based, NiP alloy	Connectors
Rhodium	Sulphate based	General electronics
Bronze	White bronze	Electronic components

Figure 16. Suitable Coating Types for Microwave Constructions (Eskelinen, H. & Eskelinen, P. 2003)

Material	Elastic Modulus [Pa]	Thermal Conductivity [W/m°C]	Thermal Expansion Coefficient [μm/m°C]
Aluminum 6061-T6	7.310E+10	155.80	24.30
Aluminum 7079-T6	7.172E+10	121.10	—-
Beryllium QMV	2.897E+11	147.10	14.94
Copper—pure	1.172E+11	392.90	16.56
Gold—pure	7.448E+10	297.70	4.39
Nickel—pure	2.207E+11	91.73	12.96
Silver—pure	7.241E+10	417.10	19.80
Steel AISI 304	1.931E+11	—-	17.82
Steel AISI C1020	2.034E+11	—-	11.34

Figure 17. Values of Modulus of Elasticity, Thermal Conductivity, and Thermal Expansion Coefficient (Eskelinen, H. & Eskelinen, P. 2003)

3.1.5 Q-Factor Measurement Techniques

Based on previous research, the importance of the Q-factor was clarified, and it has been learned that Q-factor is related to properties such as surface roughness. So, how do you quantify the Q value of RF components such as resonators?

The basic definition of Q-factor was mentioned earlier, but there is more than one way the Q-factor is expressed. Here, we refer to the method for expressing the relationship between surface roughness and Q-factor in “SURFACE EFFECT INFLUENCE ON THE QUALITY FACTOR OF MICRORESONATORS” (Shiari, B. & Najafi, K. 2013). This paper determined that the Q factor of a micro resonator with surface roughness can be calculated as follows: Q-factor is equal to the ratio of 1 to the surface dissipation factor. The resonator's equation of motion is derived from the Euler-Bernoulli beam equation. The effect of surface roughness is introduced by modifying the surface stress equation, and the Q factor decreases as surface roughness increases (inclination angle). This coincides with the actual results.

$$\frac{1}{Q} = \frac{2\delta(3b+h)}{bh}\frac{E_2^S}{E_1}$$

Figure 18. The formula for resonator surface Q factor (Shiari, B. & Najafi, K. 2013)

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

Figure 19. The Relationship Between Frequency Range and Surface Roughness in Some Radio Frequency Components (Eskelinen, H. & Eskelinen, P. (2003)

3.1.6 Summary of Literature Review Findings

The literature review provides important insights into the design, material selection, mechanical stability, and measurement techniques of ultra-low phase noise resonators. By comparing the conductivity and other characteristics of the materials, the study clarified the material selection and coating selection for the resonator cavity. Furthermore, methods that can intuitively express the Q-factor can provide a standard for evaluating the performance of resonators.

3.2 Expert Interview Results

To verify the results of the literature review and gain industry insights, the author conducted an expert interview with a leading researcher who specializes in microwave component mechanics and qualified resonators in space. Thanks again to Professor Pekka and LUT University for their support. The expert provided key comments on resonator design, material selection, and environmental factors, which inspired me a lot.

3.2.1 Resonator Cavity Structure and Surface Requirements

First, experts mentioned that the inner surface of the resonator chamber must be very smooth. If the surface is rough, electromagnetic wave scattering will increase, leading to increased power loss, reduced Q factor, and increased phase noise. “The important thing here is not the external surface but the cylindrical cavity inside the unit that defines the performance of this resonator. If we just consider phase noise, there are two things we must optimize: The surface quality of the interior should be like a polished mirror, extremely smooth. Electrical conductivity—it should be as high as possible.” This is consistent with the information in the literature.

At the same time, experts also pointed out that the equipment requires high conductivity to ensure minimal resistance loss to obtain a higher Q factor. That's right; highly conductive materials reduce resistance loss, thereby increasing the Q value. For example, the conductivity of composite conductors such as silver, copper, gold, and tin is directly related to the resonator quality factor. (Benarabi, B. et al. 2016) However, it is difficult to achieve the highest value for both characteristics, and a balance between the two characteristics is necessary in the design. “These two are not easy to meet at the same time because the best flavors are sometimes mixed with materials that are very tasty to make very Smooth.”

This is consistent with literature findings. In “Q-factor optimization for high-beta 650 MHz cavities for PIP-II,” the study also discussed the trade-off between conductivity and surface quality when optimizing Q values. (Martinello, M. et al. 2021)

3.2.2 Mechanical Stability and Space Environment Considerations

For space applications of resonators, one of the biggest challenges is how to minimize the impact of mechanical vibrations on the resonator. Experts have confirmed that sapphire holders are the first choice for stabilizing dielectric resonator elements because they provide excellent mechanical stiffness while not interfering with the electromagnetic properties of the chamber. (Liu, Y. & Zhou, Y. 2024) (Belfi, J. et al. (2010) The talks also emphasized that cosmic radiation degradation is a major long-term reliability issue. Professor Pekka explained that radiation damage reduces the conductivity of internal surfaces, causing the Q factor to drop, and in extreme cases, the oscillator completely fails. “Cosmic Radiation

Destroys the Surface, the Internal Surface of the Cavity. If that gets bad, then, in the worst case, the whole oscillator might stop. The Q-value would go so low that there would be no resonance at all."

Therefore, the choice of coating and material is important, as is the shape of the lid. The Flight Model of the Resonator Cavity has a different cover construction designed to better protect against cosmic radiation.

Factor	Effect on Q-factor	Optimization Strategy
Surface Roughness	Increases RF loss, reduces Q-factor	**Polished mirror-like surfaces** via precision machining and silver plating
Electrical Conductivity	Higher conductivity improves Q-factor	Use **silver plating** but address **oxidation concerns**
Mechanical Vibrations	Causes frequency shifts, lowering Q-factor	Use **sapphire supports** for the dielectric resonator
Cosmic Radiation	Degrades surface conductivity, reducing Q-factor	Design **radiation-resistant covers**, use **protective coatings**

Figure 20. Summary of Expert Interview Insights

3.3 DFMA for the Resonator Cavity

As mentioned earlier, the SolidWorks model is used in triangulation to perform DFMA analysis. This section analyzes the manufacturability and assembly design of the model to evaluate the manufacturing feasibility and assembly efficiency of ultra-low phase noise oscillator resonators in remote sensing satellites. DFMXpress is used for virtual manufacturing to point out issues that have arisen during design and production.

Figure 21 shows the modeling of the resonator cavity and DFMXpress analysis results.

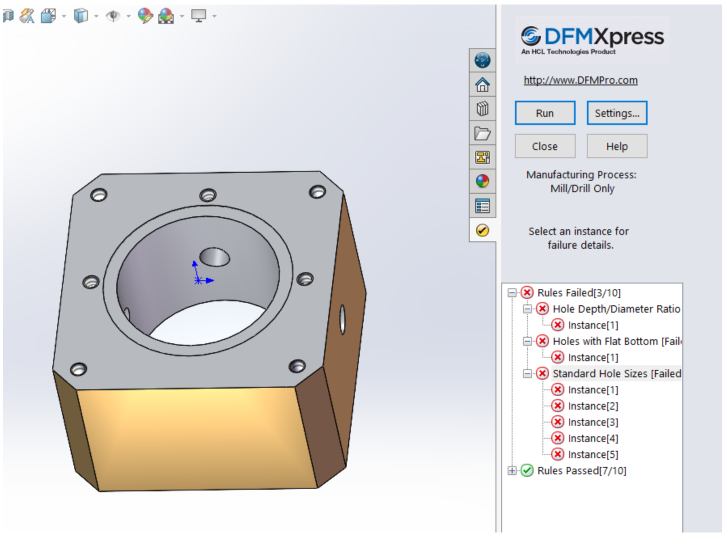


Figure 21. DFM analysis for resonator cavity

According to DFMXpress analysis, issues to be aware of in the resonator cavity manufacturing process include: the depth and diameter ratio of the hole, the normal value is 2.75; flat bottom holes are prone to problems when reaming, facing problems such as chip removal difficulties and possible center alignment errors. They should be marked, and the bottom of the hole can be processed using a special flat-bottom reamer or milling method; the recommended standard hole diameter is 0.15mm.

Among them, the depth-to-diameter ratio of holes is a common problem, and it also exists on resonator covers and PTFE busher. To effectively handle large hole diameters, especially in deep hole drilling, special treatments such as BTA drilling must be considered to ensure good surface integrity. (Strodick, S. et al. 2024)

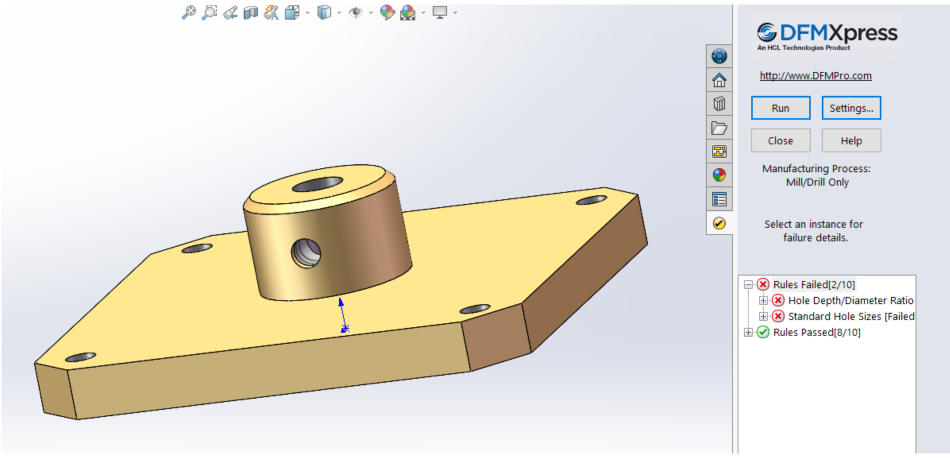


Figure 22. DFM analysis for cover of resonator cavity

When processing threaded parts, you face the problem of milling sharp internal angles. Sharp internal angles are difficult to achieve; these angles are generally changed to rounded corners or additional small-diameter holes are drilled. Or use more sophisticated processing methods, but this often means high costs.

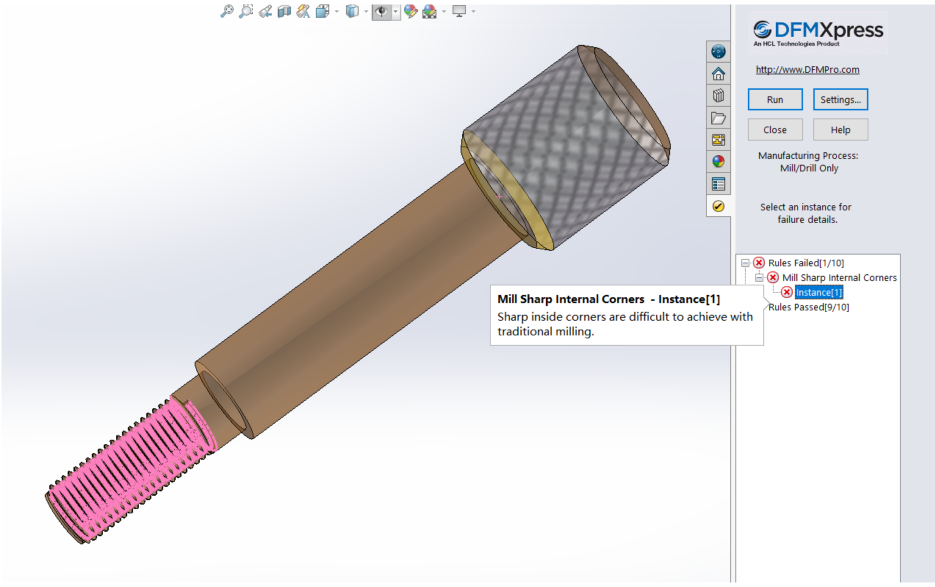


Figure 23. Problem of Mill sharp internal Corners for tuning screw

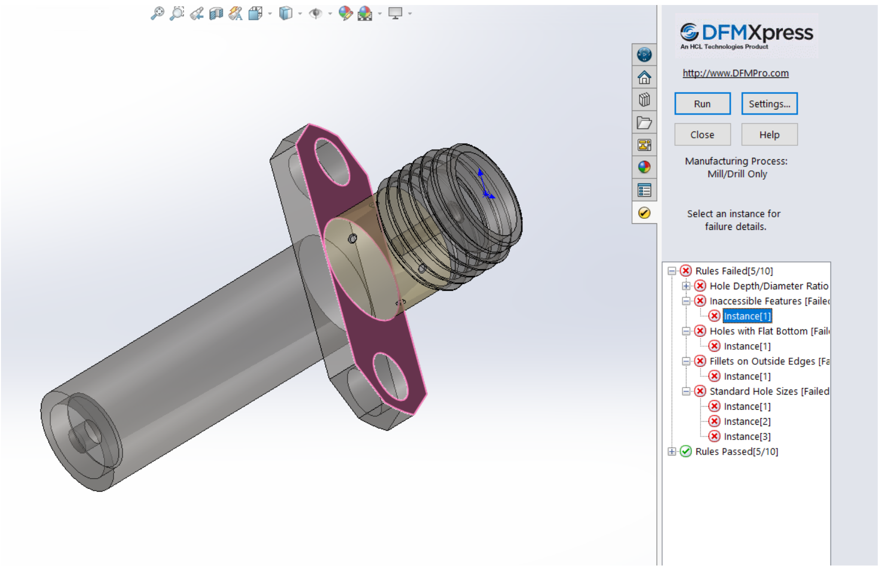


Figure 24. DFM analysis for cover of SMA connector

The SMA connector is a standardized component and is relatively special. The data comes from Amphenol RF. It faces issues with Inaccessible Features and Fillets on Outside Edges. Because SMA connectors require extremely high signal transmission, their installation tolerances must be controlled within ± 0.005 inches. Excessive errors result in difficult welding, signal attenuation, and reduced equipment performance.

In addition to using DFMXpress to analyze processing issues, material selection is also very important. By comparing literature and the SolidWorks material library, 6061-T6 (SS) was selected as the main material for the resonator chamber. Because it has an excellent balance of processability, thermal stability, and mechanical strength.

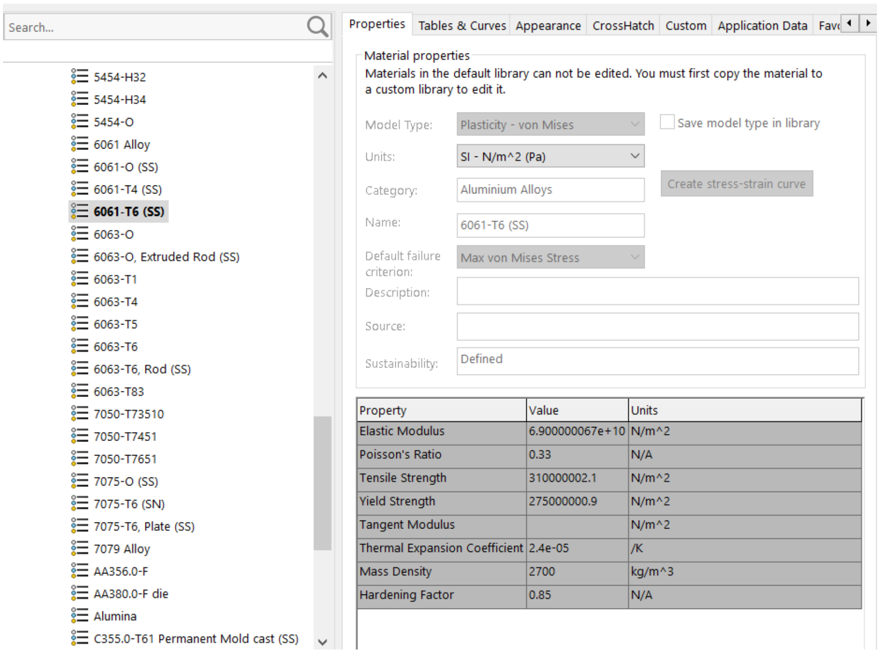


Figure 25. Properties of 6061-T6 (SS)

To enhance the manufacturability of the equipment, when drawing up the drawing, the correct view should be selected, and the dimensions, tolerance marks, surface quality requirements, and any other necessary markings should be made correctly according to the standards. Make sure the drawing is clear and understandable. The ISO-2768-FH mechanical tolerance standard is used to ensure the assembly accuracy of key components. The surface roughness of the resonator chamber affects performance, so the requirements for surface roughness are also strict.

SolidWorks CAM is then used to simulate the machining process of spare parts, as shown in the figure below the simulated machining process diagram of the main part of the resonator chamber.

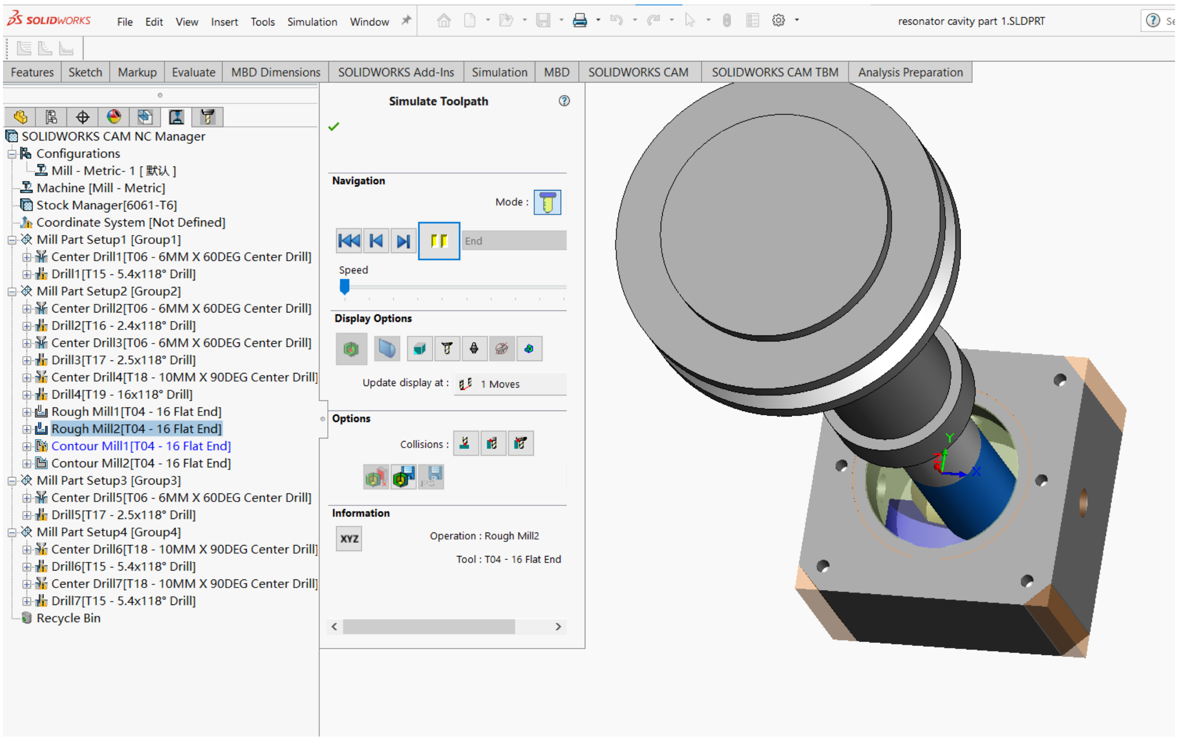
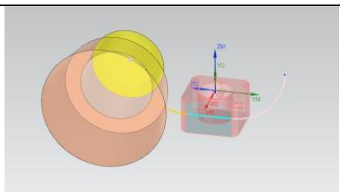
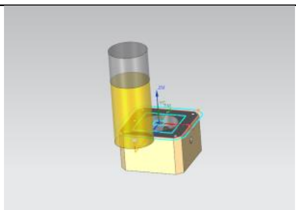
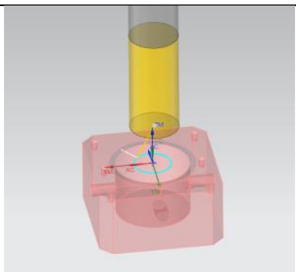
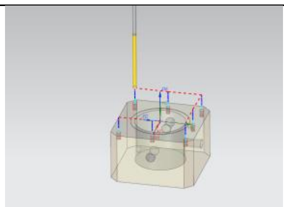
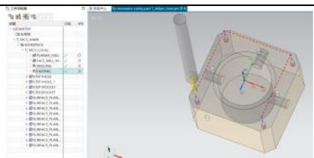
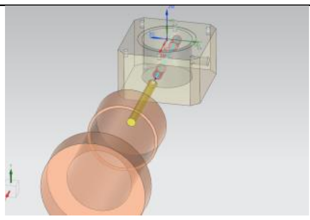
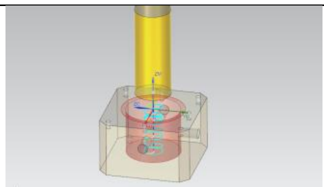


Figure 26. Simulated machining process diagram of the resonator.

SolidWorks will first extract the characteristics to be processed, then generate a processing plan and design the tool path during processing. Finally, generate a simulated processing animation. Processing is mainly divided into four groups of processing. The first group is drilling (back), the second group is milling, drilling and threading (top), the third group is drilling and threading (bottom), and finally drilling (left and right).

However, since SolidWorks CAM can only automatically recognize model features, the processing is relatively rudimentary, so the researchers used UG NX to conduct a second analysis. UG NX provides seamless integration of CAD and CAM functions, allowing users to create detailed 3D models and directly generate tool paths for machining. This integration helps reduce errors and streamlines the design-to-manufacturing workflow (). The table below shows the processing flow chart for the main part of the resonator chamber. The processing uses a three-axis machine and traditional milling and drilling methods. The table shows the time and percentage at which the rough was machined, as well as the tool selected during the simulation.

Machining stage	Figure	Tool	Simulated time	%（of total time）

Mill (External surface treatment)		Mill	03:56	46.27
Milling (Top Surface)		Mill	01:54	22.35
Face milling		Mill	00:19	3.73
Drilling		STD-drill	00:13	2.55
Tapping		TAP	00:17	3.33
Deep hole drilling		Twist drill	00:34	6.67
Hole milling		Indexable Insert Drill	01:17	15.1

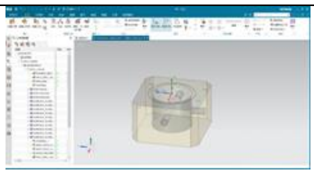
Total			08:30	100.00

Table 3: Manufacturing times for the geometries of the resonator cavity main part.

Compared to SolidWorks CAM, UG NX shows a sharper machining path.

3.4 Triangulation-based observations

The triangulation method was used to validate the findings by integrating three methods: expert interviews, literature review, and DFMA analysis. The purpose of adopting this approach is to balance the evaluation of manufacturing challenges and design optimization.

1. Expert interview results: Influence of surface roughness: Experts emphasize that internal surface roughness has a significant impact on phase noise performance. Smoother surfaces can reduce electromagnetic scattering and power loss, thereby increasing the Q factor.

The importance of material selection: Industry professionals have proven that sapphire supports are essential to minimize mechanical vibrations and reduce frequency drift in space environments.

Radiation and thermal stability: Experts emphasize that cosmic radiation reduces material properties over time. Material selection and coating methods, such as gold plating, are considered essential to ensure long-term stability.

2. Verified through literature review: Resonator coating advantages: Research has proven that silver-plated resonators have a better Q factor and lower power loss.

Effects of space conditions: Research shows that gold plating can effectively reduce the effects of cosmic radiation and improve long-term reliability.

Thermal expansion management: The literature emphasizes that the use of materials with a low coefficient of thermal expansion helps maintain frequency stability under extreme temperature changes.

3. Cross-validate with DFMA results: Processing Feasibility: DFMA simulations confirm that tight tolerances are critical to maintaining RF performance. However, some design modifications, such as increasing the corner radius, are recommended to improve manufacturability.

Fastener placement optimization: The analysis validated expert recommendations on screw placement, ensuring structural integrity and ease of assembly.

4. Final observations and suggestions: Expert insight, literature verification, and DFMA findings are combined to support proposed design modifications and ensure a balance between performance and manufacturability.

Future research should explore alternative coatings with lower surface resistance to further improve the Q factor. If prototype testing is carried out, simulations and theoretical results can be further empirically verified.

Triangulation methods ensure that research findings are fully supported, thereby reducing bias and improving the reliability of results.

4 Discussion

The content of this section is a discussion based on the results obtained earlier. In this section, the researchers summarized the main findings of the study; compared this study with previous research in the same field; and systematically analysed the reliability of this study. Finally, explain the researcher's thoughts on the future development of this field.

4.1 Key findings and conclusions

Using a triangulation method, this study proposed a resonator design scheme for ultra-low phase noise oscillators based on DFMA principles. The main findings of the study were as follows:

Surface roughness significantly affects Q factor and frequency stability. According to expert interviews and literature analysis, the inner surface must be highly polished (near mirror) to reduce surface resistance and electromagnetic loss and increase the Q value of the cavity. This is consistent with Harry Eskelinen's view that “surface treatment has a significant impact on microwave structural performance, and roughness causes reflection and power loss.” (Hati, A. et al. 2007) Material selection has a dual impact on performance and manufacturing costs. DFM analysis shows that using aluminium alloys with high conductivity can improve thermal conductivity and electromagnetic performance while ensuring processability. In areas where conductivity and corrosion resistance need to be improved, silver plating or gold plating can be used, which is supported by the “substrate and coating must be co-designed” principle proposed by professor Eskelinen. (Hati, A. et al. 2007)

The design should prioritize geometric manufacturing constraints. The SolidWorks DFMxpress report shows that structures such as sharp corners, deep holes, and non-standard threads are not conducive to CNC machining and need to be optimized through rounded corner replacement or structural reconfiguration. The three-axis UG NX simulation further improves the accuracy of the machining path. Compared with SolidWorks CAM, it generates clearer processing steps and has reference value for improving manufacturing efficiency. (Afonin, I. L. et al. (2004)

Phase noise modelling shows that increasing the Q value and output power is an effective way to reduce near-carrier phase noise. According to the Leeson model, phase noise is inversely proportional to Q factor, the higher the Q factor value, the more stable the output signal. (Nightingale, Andrea J. 2019)

4.2 Comparison and Connections with Former Research

This study maintains similarities with current research in the microwave and radio frequency fields in terms of design goals, engineering methods, and theoretical support. It confirms that the proposed DFMA-based cavity design approach is both scientifically valid and practically implementable.

First, about the importance of Q factor optimization, Martinello et al.'s research on the PIP-II high-β 650 MHz superconducting resonator indicated that increasing the Q value is the key to reducing power loss, improving cooling efficiency, and improving system frequency stability. The study used complex surface treatment processes such as N-doping (N-doping) and cold electropolishing to reduce surface resistance and improve resonator performance. Although this study focuses on room temperature resonators and does not use superconducting materials, its strategies in material selection, surface treatment, and processing accuracy are consistent with the path of improving performance in Martinello et al.'s research, all reflecting the central position of improving resonator quality factors in high-performance frequency sources. (Free, C. E. & Aitchison, C. S. 2022) Second, the noise measurement study of surface acoustic wave (SAW) resonators conducted by Vaillant et al., provided a quantitative reference for this study. Its measured phase noise in the 2.4 GHz band reached −130 dBc/Hz, and the corresponding short-term frequency stability Allan variance was as low as 10^{-9}. Although the resonator designed in this study is used in a higher frequency range, it is like the target performance, that is, a more stable frequency output is obtained by increasing the Q value. Therefore, in terms of phase noise optimization, the design ideas in this study were indirectly supported by actual engineering data. (Alekseev, S. G. et al. 2007)

Furthermore, Eskelinen et al.'s research on microwave mechanical structures indicates that in high-frequency structures such as resonators, electrical performance, machining performance, and environmental adaptability should be considered equally. In terms of material selection, it is proposed to select materials with good conductivity, processability, and corrosion resistance, such as anodized aluminium alloy, silver-plated copper, etc. In this study, aluminium 6061-T6 was selected as the main structural material, and gold-plated and silver-plated coatings were used in key areas, referring to its design ideas. (Hati, A. et al. 2007)

Finally, as a classical theory for phase noise modelling, the Leeson equation clearly indicates that increasing the Q value and output power of the resonator and using low noise factor components are effective strategies for suppressing near-carrier phase noise. The design goals of this paper are highly consistent with them, which further confirms the rationality of theoretical choices. (Nightingale, Andrea J. 2019)

4.3 Reliability Assessment of the Results

The reliability of this study was improved through a triangulation method, combined with expert interviews, simulation tools, and literature review. This multifaceted approach ensures that the conclusions are technically sound and practical.

Expert interviews and literature confirm each other: In terms of material selection, experts recommend the use of gold-plated or silver-plated copper alloy materials with excellent conductivity and thermal stability and emphasize their corrosion resistance and processability. This view is consistent with Eskelinen's theory that “highly conductive metals combined with good coatings can significantly improve the performance of high-frequency components”. This has also been mentioned in numerous documents. This type of cross-validation enhances the scientific nature of design material selection. (Hati, A. et al. 2007)

Simulations and expert recommendations for collaborative verification: The manufacturability analysis report automatically generated by SolidWorks DFMXpress clearly indicates that the design has difficult processing features such as deep holes, high length-to-diameter ratios, and sharp internal angles. At the same time, experts also pointed out that these characteristics can easily cause processing deformation and assembly errors. On this basis, the design makes targeted modifications to the geometric structure, such as rounded internal angles and standardized threaded holes, reflecting an effective combination of theory and practice.

Response analysis of existing literature: Through analysis combined with the Leeson model, the correlation between phase noise control and structural optimization was found, and various aspects from frequency performance to structural characteristics were analysed. This helped verify the reliability of the results. This fusion of multifaceted information makes the results more logical and practical.

Simultaneous iteration of drawings and 3D models: Before generating manufacturing drawings, this study visually verified the cooperation between components through 3D modelling (SolidWorks) several times to ensure that the design plan has good assembly compatibility in actual manufacturing. Simulating the processing process with UG NX also verified the practicality of the study.

In summary, the research was not only based on theoretical analysis but also combined engineering feedback and actual modelling to form a relatively stable process and analysis system, laying a solid foundation for subsequent physical manufacturing and testing.

	Expert Interview	Laboratory experiment (Solidworks)	Literature review	Triangulation
Validity	Ask questions to expert during meetings and obtain expert opinions to verify the correctness of design ideas.	Verify the practical viability of the design through SolidWorks and UG NX modeling simulations.	Search past journals and refer to the models and methods used in them to ensure that the methods used have sufficient theoretical basis and enhance the validity of the methods.	Multi-method verification increases the effectiveness of the overall results.
Reliability	A unified list of questions has been drawn up, covering various aspects such as material selection and manufacturing processes, to obtain professional opinions from professionals on the feasibility of resonator design and manufacturing, to ensure the reliability of research results.	The SolidWorks model is based on geometric parameters obtained from multiple measurements, and all boundary conditions and other settings of the model are strictly recorded and reused. Every simulation can be completely reproduced and meets the "experimental repeatability" standard in reliability.	Find literature through high-impact databases such as LUT primo, IEEE, and Scopus. Reference documents are published, peer-reviewed journals, and widely quoted papers within the past 15 years to ensure the scientific nature and reproducibility of the materials.	Each method is cross-validated multiple times, such as comparing expert suggestions with existing literature arguments to support modeling and simulation to enhance the reliability of the results.
Sensitivity	To test the stability and sensitivity of expert opinions, I cross-discussed the topic of "material selection" in different issues. Experts' responses to other research projects were also recorded. In similar fields, the answers given by experts are related and similar. The results showed that expert opinions are less sensitive in the microwave field, which enhances the stability of research findings.	To evaluate the sensitivity of the simulation model, I tested the model with variables and comparative analysis. Variables such as material type, geometric parameters, and boundary conditions were analyzed to identify the effects of different variables in the cavity structure design on performance.	The study compared numerical differences of the same parameter in different literature, analyzed the application boundaries of the model/theoretical basis, excluded some literature that relied on certain uncertain information, and verified the sensitivity of different documents to key factors	Triangular verification can identify the interference of variable factors in research results and improve the stability of research results.
Error analysis	Experts may be based on empirical judgments rather than experimental data and may have subjective opinions or inconsistencies. I've set up the questions as clearly as possible to avoid miswording. It also reduces errors by comparing expert answers to other researchers' questions.	All 3D models are built based on actual design drawings, avoiding unnecessary geometric simplifications. The dimensional accuracy is controlled within 0.01 mm, and the key chamber structure uses engineering tolerance inputs. Material properties, boundary conditions, etc. are analyzed many times and numerical comparison analysis is recorded.	By comparing experimental methods, data collection and calculation processes in different literature; reducing the range of data fluctuations, methodological limitations. Reduce errors and improve the stability of research findings through multi-source data comparison.	By repeatedly comparing the differences obtained by each method and continuously optimizing the implementation of the different methods, system errors can be identified and reduced.
Accuracy	Evaluating the consistency of information and judgments provided by experts with facts, practical applications, or other data sources, and exploring ways to improve the accuracy of this information is important to enhance the credibility of the study. The researchers cross-compared expert suggestions with authoritative literature to improve accuracy.	All 3D models are constructed with reference to real equipment, and the key dimensions are controlled within ± 0.01 mm to ensure consistency between the geometric modeling and the actual structure. Material parameters are from authoritative data sources. Comparative verification of simulation results with theory/measured values.	In the literature review process, this study paid special attention to the accuracy of data and models to ensure that the cited materials provide a credible foundation for design and simulation. Prioritize research using original documents and authoritative sources. Many documents were selected to compare and analyze the consistency of the results of different documents, and literature within a reliable range was selected.	The consistency of multi-method verification enhances the accuracy of research results. Model analysis and literature selection have gone through multiple rounds of revisions to improve accuracy.
Saturation	During the meeting, the researchers designed structured multi-topic outlines and conducted in-depth discussions on various core issues such as material selection, structural design, and error control.	The simulation experiments carried out more than 10 sets of modeling tests under different structures, materials and operating conditions, covering all design variables. In subsequent simulations, the simulation model output stabilized.	The literature review system analyzed many studies on ultra-low phase noise resonators over the past 15 years, covering key topics such as theoretical modeling, material optimization, and manufacturing strategies. Finally, literary opinions tend to converge, new literature fails to provide significantly different or challenging new arguments, and information tends to be saturated.	This study uses triangular verification to integrate three types of data sources: expert opinions, simulation results, and literature. On the core issues, the findings of the three types of data are highly consistent, and there is no significant conflict, indicating that the findings have been fully verified from multiple angles.

Table 4: Reliability analysis of results.

This study comprehensively assessed the credibility of the research process through systematic analysis of the four main research methods, expert interviews, SolidWorks simulation experiments, literature review, and triangular verification, in the six dimensions of effectiveness, reliability, sensitivity, error analysis, accuracy, and saturation. The analysis results showed that the methods complement each other in different dimensions.

4.4 Topics for Future Research

Although this study has established a complete design and manufacturing framework, there is still potential for further research and improvement directions, including:

Physical prototype manufacturing and performance testing: All current performance predictions are based on theoretical modelling and numerical simulation, and there is no actual data verification. Subsequently, CNC machining and surface treatment experiments can be carried out based on this design to measure the actual Q value, phase noise, and temperature drift performance, thereby further verifying the accuracy of the theoretical model.

Microgravity and space environment impact simulation: Since the target application environment is a remote sensing satellite orbital system, its microgravity, thermal circulation, and electromagnetic interference environment is significantly different from the ground. Thermal-mechanical coupling simulation and electromagnetic compatibility analysis are expected to be carried out in conjunction with finite element software to predict the risk of structural deformation and frequency drift.

Connection structure and fastening process optimization: The bolts and welding interfaces currently used in research equipment may have the risk of loosening and gas escaping in vacuum. The researchers believe that future research may consider introducing a solderless self-locking connection structure or flexible structure to improve long-term stability.

Interdisciplinary joint testing: Researchers believe that research on microwave equipment can cooperate with electromagnetic testing teams to build test platforms on spectrometers/phase noise analysers to obtain key frequency domain parameters and provide accurate parameter support for the next step of oscillator system integration.

5 Summary

This study focuses on how to apply triangulation to DFMA analysis of the resonant cavity of an ultra-low phase noise oscillator. A resonator is a key microwave electronic component that stores electromagnetic energy by establishing resonance conditions and generates stable oscillations at specific frequencies. In the ultra-low phase noise oscillator of remote sensing radar satellites, the resonator plays a key role, including providing a frequency reference standard for the entire system, filtering out noise components, and directly affecting the detection accuracy and performance of the satellite radar system.

The main research goals are to propose design changes through DFMA analysis to improve the manufacturability of the resonator chamber, evaluate material selection based on the aerospace properties of the components, and determine the key tolerances required to achieve optimal performance. The study aims to minimize phase noise, maximize the Q factor, and ensure thermal stability and manufacturability under extreme conditions in outer space.

The study used triangulation methods from literature reviews, expert interviews, and SolidWorks analysis to cross-validate findings with theoretical depth, practical relevance, and technical validation. This approach validates DFMA-driven design improvements and ensures that decisions are based on measurable results.

The main findings show that selecting high-conductivity aluminium alloy and high-quality silver-plated coatings can improve the overall conductivity and surface cleanliness of the components, effectively increase the Q value of the components, and reduce the phase noise generated. The modification methods are all based on CNC machining using SolidWorks and UG NX simulations, which is the only way to achieve defined tolerances. By applying DFMA principles, it is possible to simulate the manufacturing process, but further analysis of all design changes is required to ensure performance. This paper lays the foundation for further RF simulation and physical prototyping with tests.

References

Nightingale, Andrea J. (2019) Triangulation, International Encyclopedia of Human Geography, Second Edition, pp. 477 - 480

Free, C. E. & Aitchison, C. S. (2022) RF and microwave circuit design : theory and applications. [Online]. Hoboken, New Jersey: John Wiley & Sons, Inc.

Martinello, M. et al. (2021) Q-factor optimization for high-beta 650 MHz cavities for PIP-II. Journal of applied physics. [Online] 130 (17),

Jean-Michel Le Floch et al. (2013) Electromagnetic properties of polycrystalline diamond from 35K to room temperature and microwave to terahertz frequencies. arXiv.org. [Online]

Hati, A. et al. (2007) 'Vibration Sensitivity of Microwave Components', in 2007 IEEE International Frequency Control Symposium Joint with the 21st European Frequency and Time Forum. [Online]. 2007 IEEE. pp. 541–546.

Eskelinen, H. & Eskelinen, P. (2003) Microwave component mechanics. 1st ed. Boston, MA: Artech House.

Maree, J. et al. (2013) ‘Low phase noise cylindrical cavity oscillator’, in 2013 Africon. [Online]. 2013 IEEE. pp. 1–5.

Cai, Z. et al. (2020) Ultra-low phase noise oscillator employing mixed electric and magnetic coupling resonator. Microwave and optical technology letters. [Online] 62 (5), 1914–1919.

Torokhtii, K. et al. (2018) Q-factor of microwave resonators: calibrated vs. uncalibrated measurements. Journal of physics. Conference series. [Online] 1065 (5), 52027-.

Alekseev, S. G. et al. (2007) A procedure for measuring the Q factor of and attenuation in microwave composite acoustic resonators. Journal of communications technology & electronics. [Online] 52 (8), 938–942.

Vaillant, E. et al. (2017) Phase noise measurements of surface acoustic wave resonators at 2.4 GHz’, in 2017 Joint Conference of the European Frequency and Time Forum and IEEE

International Frequency Control Symposium (EFTF/IFCS). [Online]. 2017 IEEE. pp. 595–597.

Shiari, B. & Najafi, K. (2013) Surface effect influence on the quality factor of microresonators’, in 2013 Transducers & Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS & EUROSENSORS XXVII). [Online]. 2013 IEEE. pp. 1715–1718.

Zhang, M. & Llaser, N. (2021) Review of Resonator’s Q-Factor Measurement With Focus on Design of Analog and Mixed Circuits for In-Situ Measurement. IEEE open journal of circuits and systems. [Online] 2577–586.

Afonin, I. L. et al. (2004) Q-factor measurement of roll-wave resonator, in 2004 14th International Crimean Conference ‘Microwave and Telecommunication Technology’ (IEEE Cat. No.04EX843). [Online]. 2004 IEEE. pp. 638–639.

Zhang, E. G. & Wang, L. (2016) Relevant Applications of Tools in UG NX CAM Module. MATEC web of conferences. [Online] 632017-.

Bogdanov, A. A. et al. (2019) ‘High-Q states in subwavelength dielectric resonators forming in strong mode coupling regime’, in 2019 International Conference on Electromagnetics in Advanced Applications (ICEAA). [Online]. 2019 IEEE. pp. 0863–0863.

Granchi, N. et al. (2023) Q Factor Optimization of Modes in Ordered and Disordered Photonic Systems Using Non-Hermitian Perturbation Theory. ACS photonics. [Online] 10 (8), 2808–2815.

Shankar, A. et al. (2014) ‘Impact of gamma irradiation on GaN/sapphire surface acoustic wave resonators’, in 2014 IEEE International Ultrasonics Symposium. [Online]. 2014 IEEE. pp. 2560–2563.

Sariri, K. (2006) ‘Extreme temperature/radiation tolerant crystal oscillator for high reliability space applications’, in 2006 IEEE Aerospace Conference. [Online]. 2006 IEEE. p. 7 pp.-.

Qiao, Y. et al. (2022) Stabilization of electrostatic MEMS resonators using a stochastic optimal control. Chaos, solitons and fractals. [Online] 154111702-.

Woods, K. N. et al. (2017) Tunable high-κ Zr x Al 1−x O y thin film dielectrics from all-inorganic aqueous precursor solutions. RSC advances. [Online] 7 (62), 39147–39152.

YANG, J. C. & DE GROH, K. K. (2010) Materials Issues in the Space Environment : Materials issues in the space environment. MRS bulletin. 35 (1), 12–16.

Guo, C. et al. (2024) Radio-Frequency Conductivity Evaluation Method Based on Surface/Interface Scattering of Metallic Coatings. Coatings (Basel). [Online] 14 (5), 599-.

Hyie, K. M. et al. (2022) ‘Compatibility Study on Cobalt Alloy Coating Due to Different Current Distribution in Electroplating’, in Proceedings of the 3rd Malaysian International Tribology Conference. [Online]. Singapore: Springer. pp. 170–173.

Benarabi, B. et al. (2016) Microwave characterization of electrical conductivity of composite conductors by half-wavelength coplanar resonator. Progress in Electromagnetics Research Letters, 60, pp.73–80.

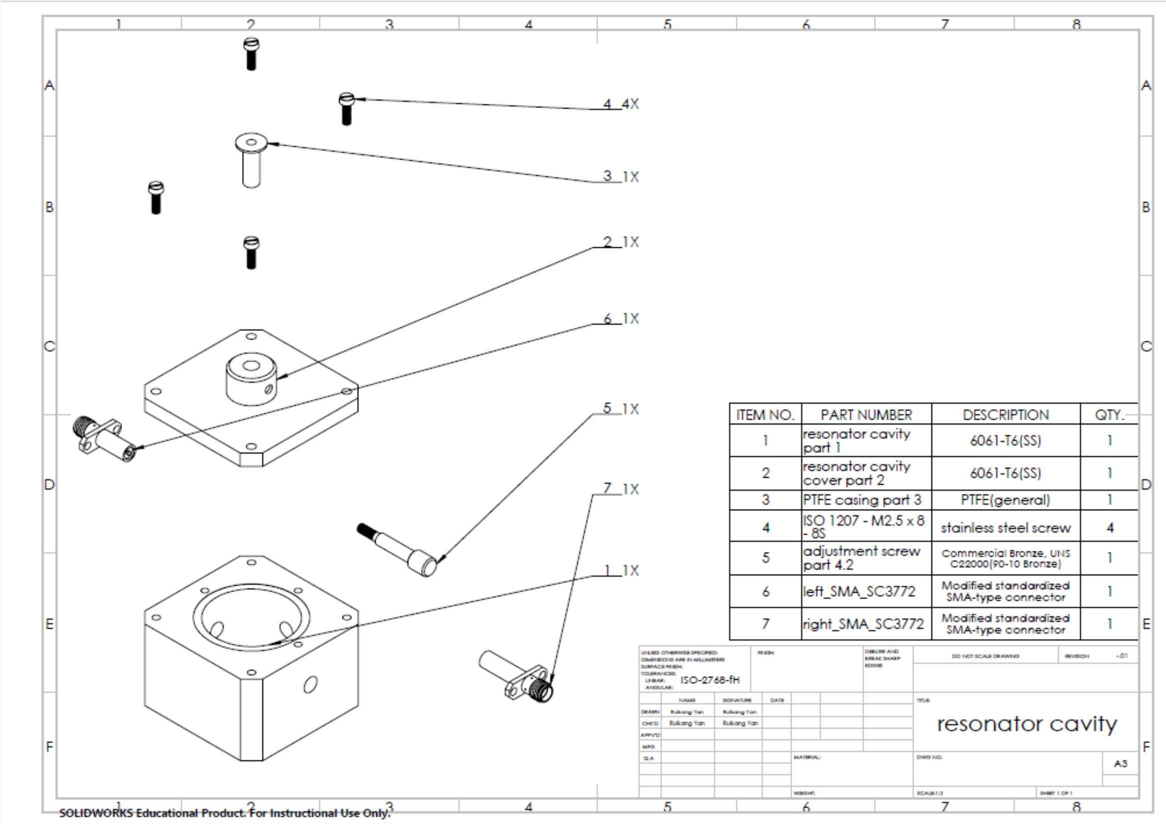
Liu, Y. & Zhou, Y. (2024) A high integration side-fed rectangular microstrip antenna based on the sapphire substrate. Journal of physics. Conference series. [Online] 2849 (1), 12139-.

Belfi, J. et al. (2010) Thermal control of a dual mode parametric sapphire transducer. IEEE transactions on ultrasonics, ferroelectrics, and frequency control. [Online] 57 (1), 121–125.

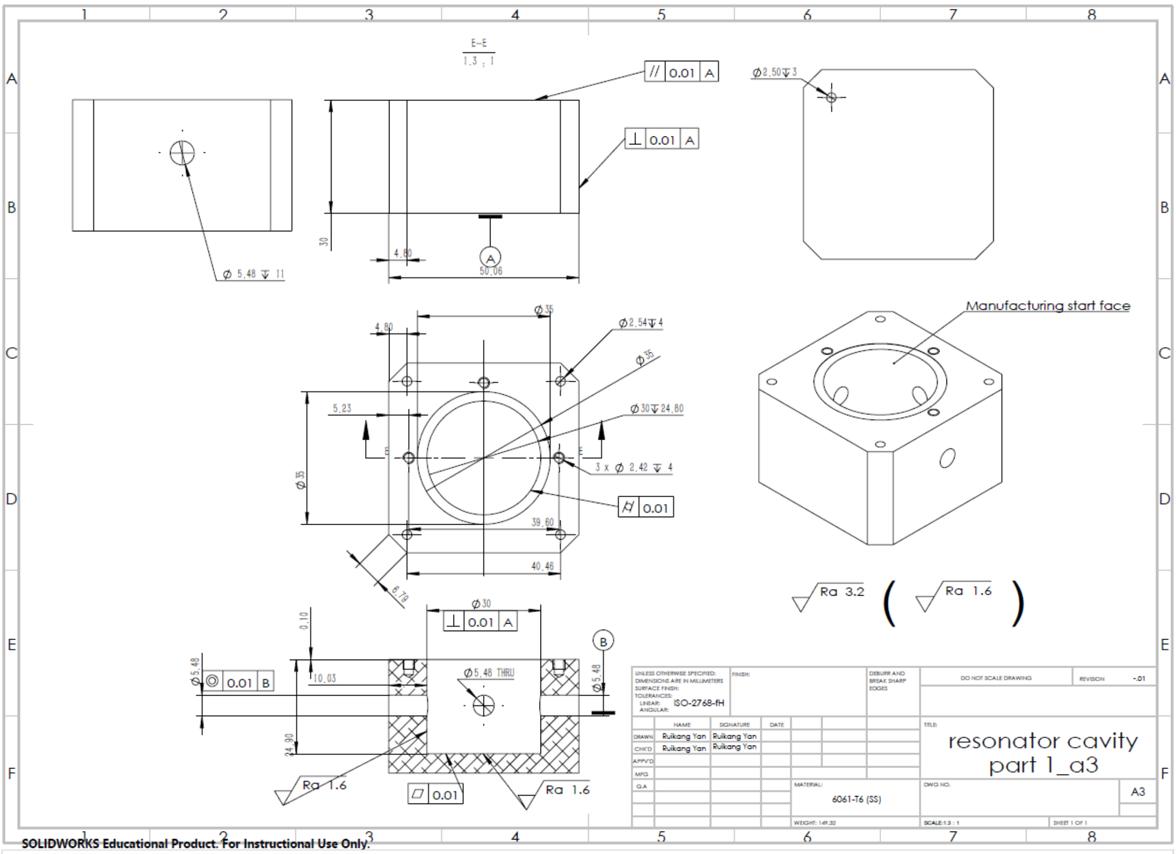
Strodick, S. et al. (2024) Subsurface conditioning in BTA deep hole drilling for improved component performance. Production engineering (Berlin, Germany). [Online] 18 (2), 299–317.

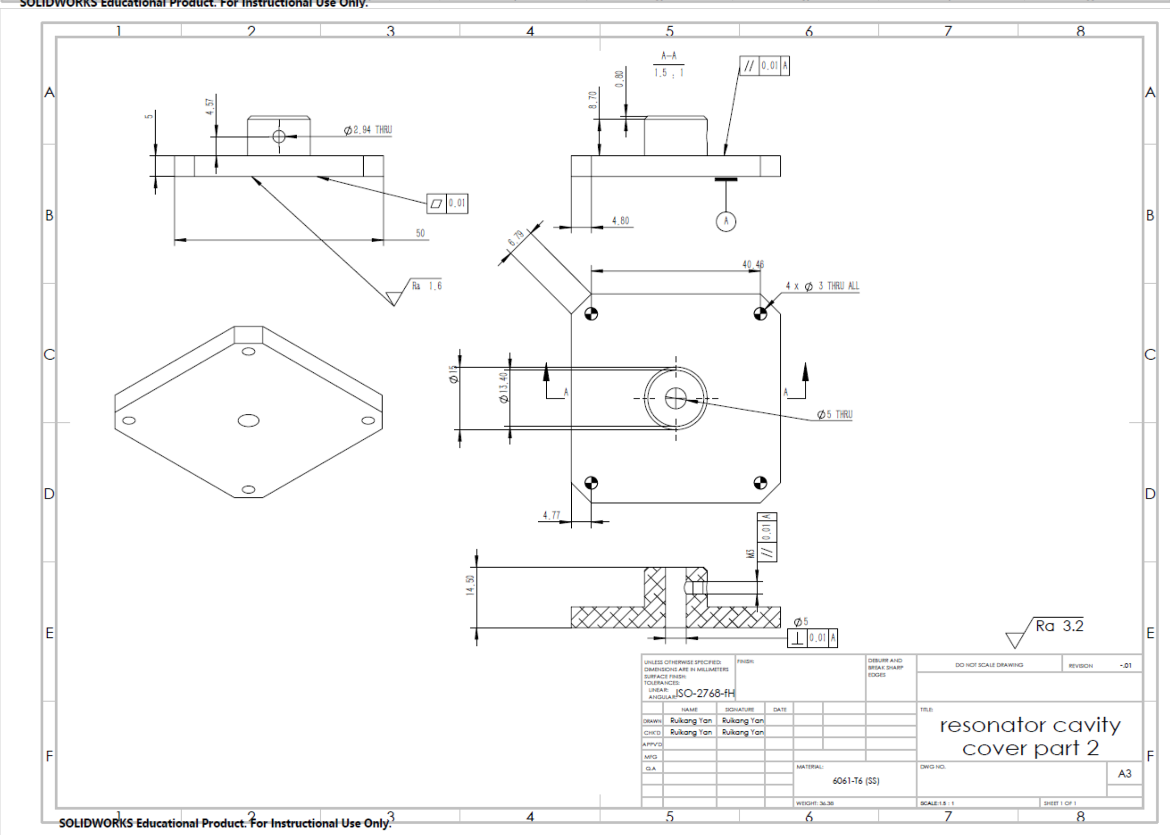
Pekka Eskelinen (2024), expert interview

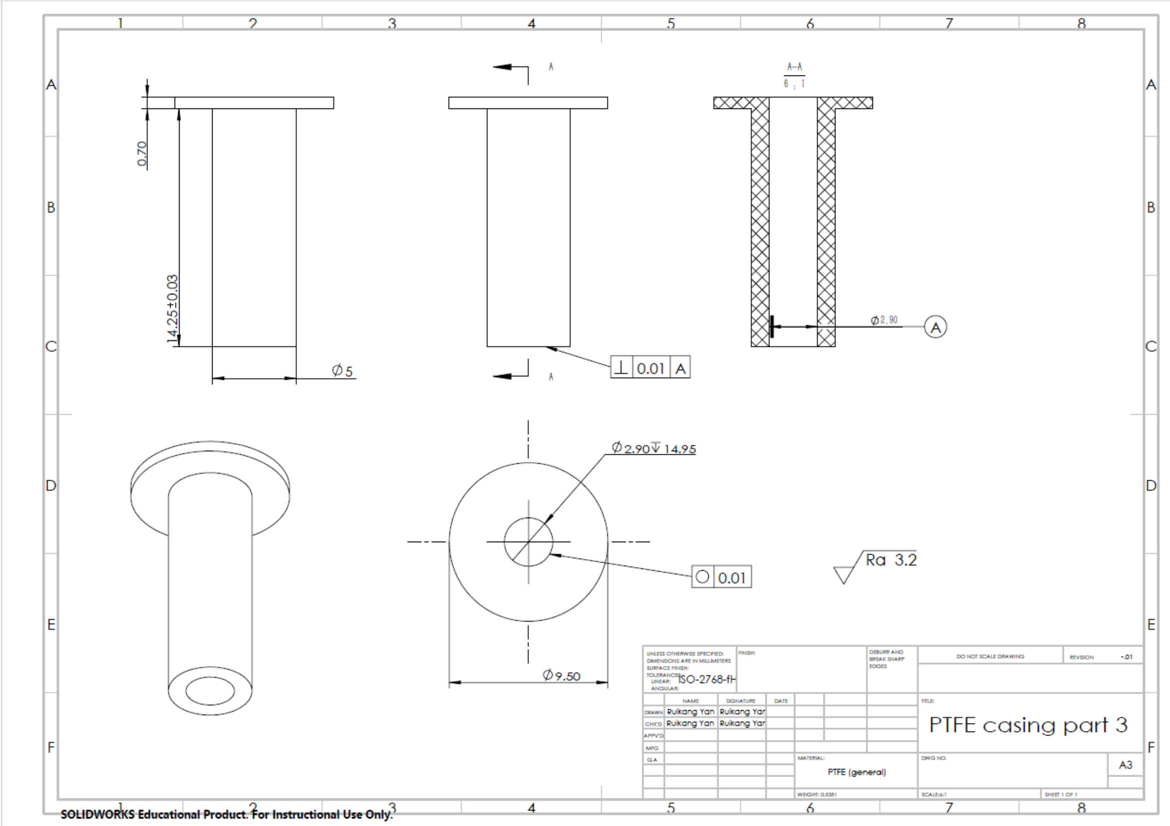
Appendix 1: Explosion view



Appendix 2.Technical Drawings for each parts



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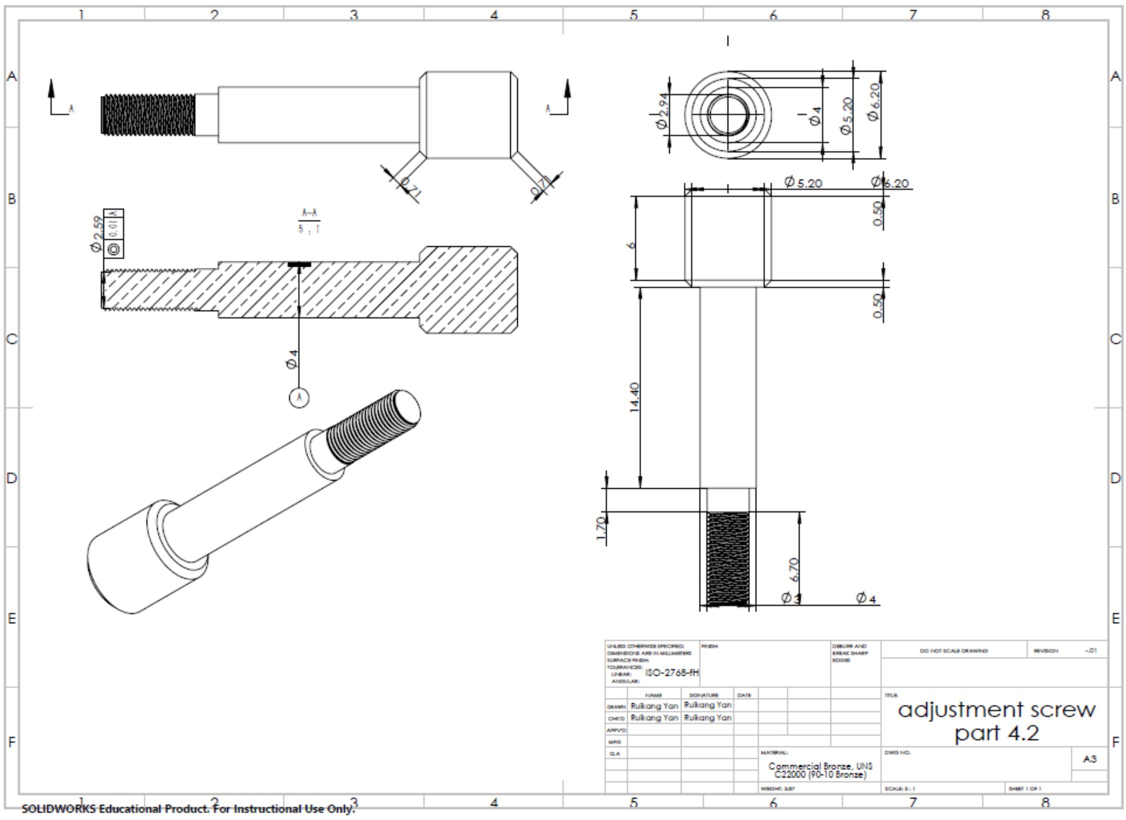
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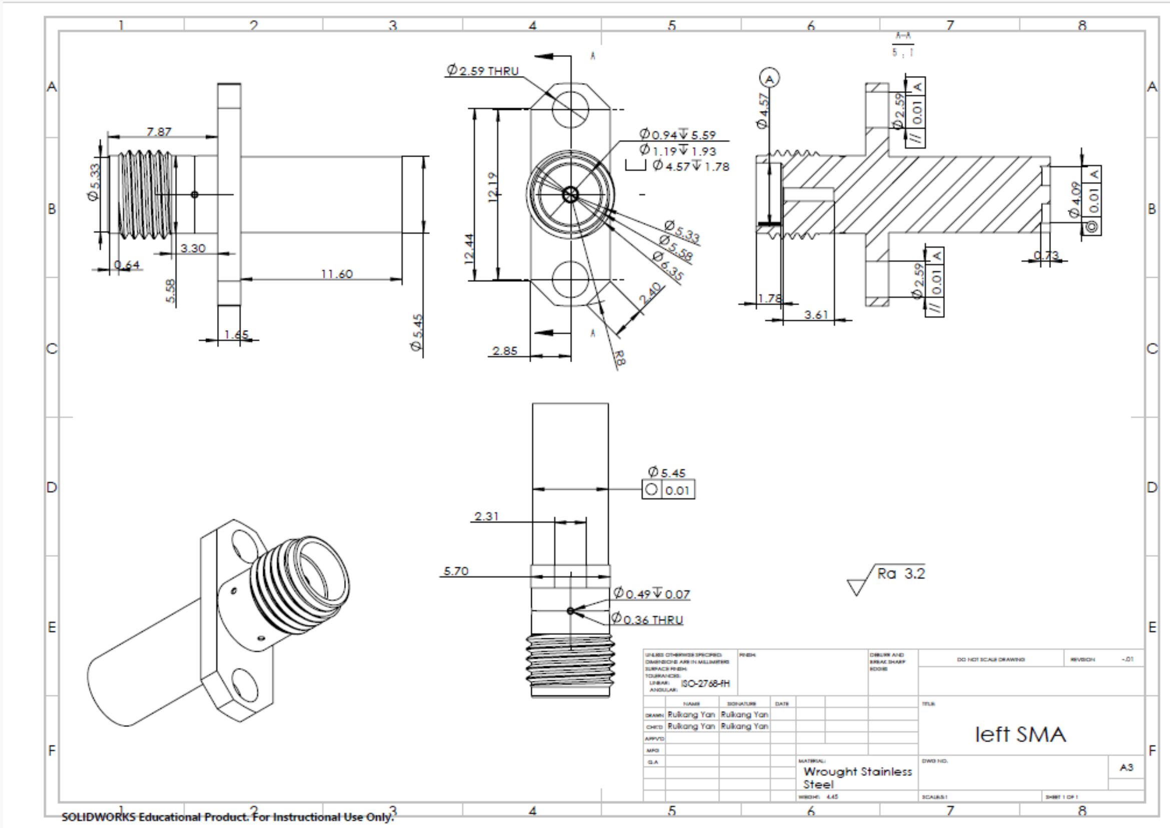
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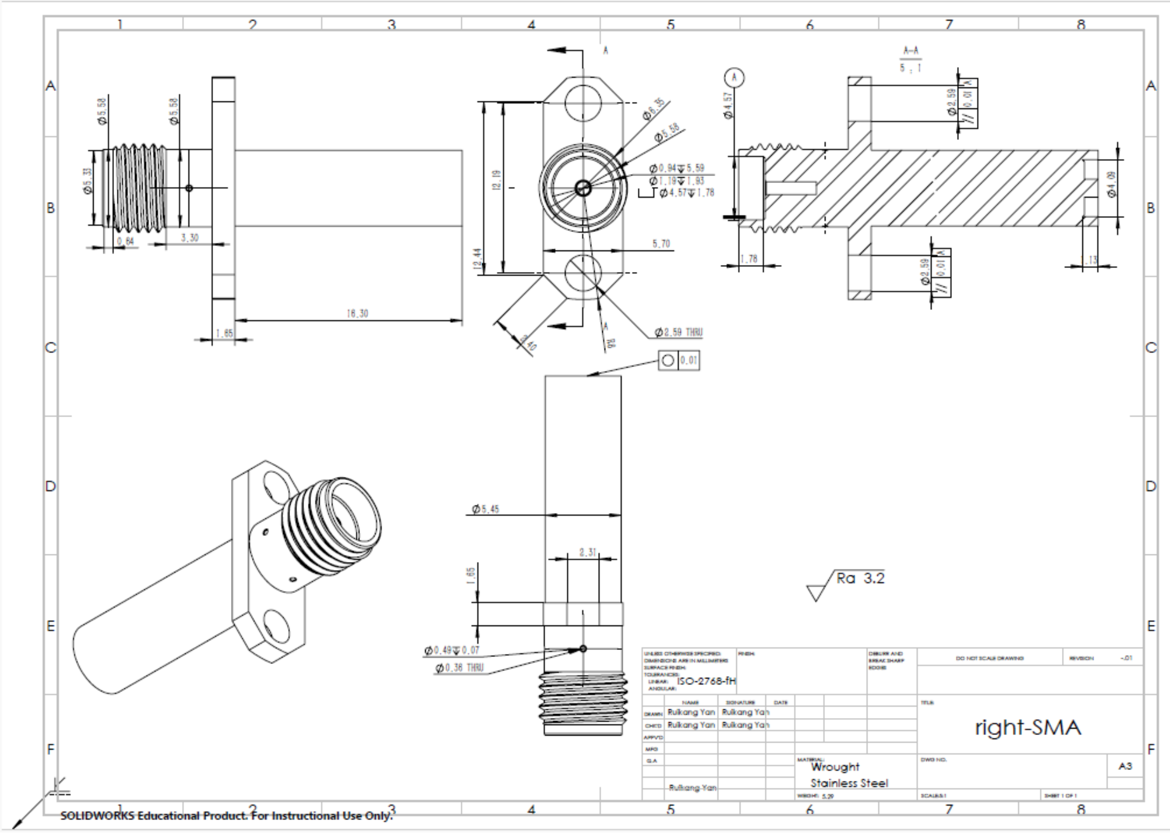
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Appendix 3.Analysis table

	Expert Interview	Laboratory experiment (Solidworks)	Literature review	Triangulation
Validity	Ask questions to expert during meetings and obtain expert opinions to verify the correctness of design ideas.	Verify the practical viability of the design through SolidWorks and UG NX modeling simulations.	Search past journals and refer to the models and methods used in them to ensure that the methods used have sufficient theoretical basis and enhance the validity of the methods.	Multi-method verification increases the effectiveness of the overall results.
Reliability	A unified list of questions has been drawn up, covering various aspects such as material selection and manufacturing processes, to obtain professional opinions from professionals on the feasibility of resonator design and manufacturing, to ensure the reliability of research results.	The SolidWorks model is based on geometric parameters obtained from multiple measurements, and all boundary conditions and other settings of the model are strictly recorded and reused. Every simulation can be completely reproduced and meets the "experimental repeatability" standard in reliability.	Find literature through high-impact databases such as LUT primo, IEEE, and Scopus. Reference documents are published, peer-reviewed journals, and widely quoted papers within the past 15 years to ensure the scientific nature and reproducibility of the materials.	Each method is cross-validated multiple times, such as comparing expert suggestions with existing literature arguments to support modeling and simulation to enhance the reliability of the results.
Sensitivity	To test the stability and sensitivity of expert opinions, I cross-discussed the topic of "material selection" in different issues. Experts' responses to other research projects were also recorded. In similar fields, the answers given by experts are related and similar. The results showed that expert opinions are less sensitive in the microwave field, which enhances the stability of research findings.	To evaluate the sensitivity of the simulation model, I tested the model with variables and comparative analysis. Variables such as material type, geometric parameters, and boundary conditions were analyzed to identify the effects of different variables in the cavity structure design on performance.	The study compared numerical differences of the same parameter in different literature, analyzed the application boundaries of the model/theoretical basis, excluded some literature that relied on certain uncertain information, and verified the sensitivity of different documents to key factors	Triangular verification can identify the interference of variable factors in research results and improve the stability of research results.
Error analysis	Experts may be based on empirical judgments rather than experimental data and may have subjective opinions or inconsistencies. I've set up the questions as clearly as possible to avoid miswording. It also reduces errors by comparing expert answers to other researchers' questions.	All 3D models are built based on actual design drawings, avoiding unnecessary geometric simplifications. The dimensional accuracy is controlled within 0.01 mm, and the key chamber structure uses engineering tolerance inputs. Material properties, boundary conditions, etc. are analyzed many times and numerical comparison analysis is recorded.	By comparing experimental methods, data collection and calculation processes in different literature; reducing the range of data fluctuations, methodological limitations. Reduce errors and improve the stability of research findings through multi-source data comparison.	By repeatedly comparing the differences obtained by each method and continuously optimizing the implementation of the different methods, system errors can be identified and reduced.
Accuracy	Evaluating the consistency of information and judgments provided by experts with facts, practical applications, or other data sources, and exploring ways to improve the accuracy of this information is important to enhance the credibility of the study. The researchers cross-compared expert suggestions with authoritative literature to improve accuracy.	All 3D models are constructed with reference to real equipment, and the key dimensions are controlled within ± 0.01 mm to ensure consistency between the geometric modeling and the actual structure. Material parameters are from authoritative data sources. Comparative verification of simulation results with theory/measured values.	In the literature review process, this study paid special attention to the accuracy of data and models to ensure that the cited materials provide a credible foundation for design and simulation. Prioritize research using original documents and authoritative sources. Many documents were selected to compare and analyze the consistency of the results of different documents, and literature within a reliable range was selected.	The consistency of multi-method verification enhances the accuracy of research results. Model analysis and literature selection have gone through multiple rounds of revisions to improve accuracy.
Saturation	During the meeting, the researchers designed structured multi-topic outlines and conducted in-depth discussions on various core issues such as material selection, structural design, and error control.	The simulation experiments carried out more than 10 sets of modeling tests under different structures, materials and operating conditions, covering all design variables. In subsequent simulations, the simulation model output stabilized.	The literature review system analyzed many studies on ultra-low phase noise resonators over the past 15 years, covering key topics such as theoretical modeling, material optimization, and manufacturing strategies. Finally, literary opinions tend to converge, new literature fails to provide significantly different or challenging new arguments, and information tends to be saturated.	This study uses triangular verification to integrate three types of data sources: expert opinions, simulation results, and literature. On the core issues, the findings of the three types of data are highly consistent, and there is no significant conflict, indicating that the findings have been fully verified from multiple angles.

Questions Q1-Qn, to which the answers are searched for	Reference #1	Reference #2	Reference #3	Reference #4	Reference #5	Reference #6	Reference #7	Reference #8	Reference #9…	Reference #N	Summarized observations to integrate the final answers to each question
Q1：What unusual requirements do space conditions place on DFM for components of resonators used in ultra-low phase noise oscillators?			√	√	√						Equipment needs to withstand extreme temperature changes and the long-term effects of cosmic rays. DFM design must consider differences in mechanical vibration and thermal expansion, select materials with low vibration sensitivity, and significantly reduce the impact of mechanical vibration on phase noise through mechanical damping and active damping techniques.
Q2：What are the main challenges in maintaining mechanical stability and dimensional tolerances of resonators in extreme space environments?				√	√	√				√	Key challenges include: Mechanical vibration and shock (frequency can be fine-tuned using tuning screws [5].) Temperature changes (using materials with a low coefficient of thermal expansion [3]) Dimensional tolerance control (use of aluminum housings (Ref. [10]) and fiberglass positioners [4] to achieve fine tolerance control of mechanical components)
Q3：How does the choice of coating material affect performance?	√		√		√						Highly conductive coatings, such as silver plating, can significantly reduce surface resistance and increase the Q factor. Appropriate coating materials can maximize the reflectivity of electromagnetic waves and reduce power loss. [3] In space applications, gold plating also provides protection against corrosion and cosmic rays to ensure stable long-term performance.
Q4：How to quantify the Q-factor value of RF components such as resonators?	√	√				√	√	√	√	√	1. The unloaded Q factor (QU) is calculated from insertion loss (IL) and resonance frequency (f). 2. Using microwave reflectometer (microwave reflectometer) and resonance spectrum analysis methods, the Q factor was accurately calculated by measuring the S parameter (S11) and fitting the phase slope.
Q5：How do the material selection and geometric design of the resonator affect its thermal stability?	√	√	√	√		√	√		√	√	In design, priority should be given to materials with low thermal expansion coefficients and multi-layer structures, plus designs such as tuning screws and silver plating on harmonic chambers to achieve coordination of thermal expansion and minimize stress effects.
Qn											
Summarized observations about the relevance of each reference	The effects of coating material selection on conductivity and surface smoothness are provided, and the definition and measurement methods of the Q factor are explained in detail.	Through the method of optimizing the Q factor, the effects of material selection and surface treatment on improving the thermal stability and Q factor of the resonator were demonstrated.	The excellent electromagnetic properties of polycrystalline diamond in high frequency and low temperature environments have been studied, and its advantages in improving the thermal stability and conductivity of resonators have been proven.	Methods for designing and manufacturing microwave components under spatial conditions are provided, and the system explains the effects of mechanical stability, material selection, and coating technology on performance.	A method for achieving mechanical stability by tuning screws is provided, and how to optimize the phase noise performance of a resonator by quantifying the Q factor is shown.	Through electromagnetic coupling design, methods for improving the Q factor and achieving ultra-low phase noise are shown, which is suitable for resonator design in space applications.	The vibration sensitivity of microwave components has been studied, and specific methods for maintaining mechanical stability in a space environment, particularly in terms of vibration suppression, have been proposed.	The effects of calibrated and uncalibrated methods on the accuracy of the Q factor measurement were compared, and a reliability analysis of the experimental methods was provided.	An experimental method for measuring the Q factor using a microwave reflectometer is proposed, especially for application in composite acoustic resonators, which supports multi-frequency applications.	The phase noise performance of SAW resonators was studied, and mechanical stability under extreme temperature conditions and the effectiveness of achieving ultra-low phase noise through carrier suppression technology were verified.	