3D-printed microwave cavities for atomic clock applications

Benefits of additive manufacturing for atomic clocks

Competences:

In order to exploit the potential of 3D-printed (additive manufactured) microwave cavities for highly demanding atomic clock applications, one industrial and two academic partners joined forces:

SWISSto12 SA contributed its considerable experience with design and additive manufacturing of passive microwave components and antennas up to 110 GHz, for aeronautical and space applications.

EPFL Microwaves and Antennas Group (MAG) contributed its expertise in design, simulation, and measurements of microwave devices such as antennas and cavities.

Laboratoire Temps-Fréquence (LTF) at University of Neuchâtel contributed its long-standing expertise on the development and characterization of atomic clocks, including compact vapour-cell clocks.

Summary:

Atomic clocks are the most precise timepieces existing today. A variety of atomic clocks are uniquely provided by Swiss specialized industry and they constitute one of the Priority Areas of the Swiss Space Implementation Plan. The vast majority of today's existing atomic clocks relies on microwave cavity resonators for applying the interrogating microwave radiation in a well-controlled way to the atomic sample serving as ultra-stable time reference. Conventional manufacturing of such cavities generally relies on expensive precision machining and time-consuming assembly of metal parts. In contrast, 3D-printing techniques are known to considerably simplify and accelerate the manufacturing and assembly of the fabricated parts. By using a proprietary SWISSto12 3D-printing process, one completely eliminates the need for the cavity assembly, and significant reduction in cavity mass can be reached as well. In this project we investigated on the suitability of 3D-printing for the manufacturing of microwave cavities with complex geometries, for atomic clock applications.

Results:

For demonstrating the 3D-printing approach, a microwave cavity for compact high-performance vapour-cell atomic clocks was selected. Based on a design previously developed by LTF and MAG for conventional cavities, a design showing a six-electrode geometry was established. Fully operational monoblock cavity structures with electrodes were manufactured, using Stereolithography (SLA) of a polymer followed by metal coating, and using Selective Laser Melting of aluminium (SLM), Figure 1a. These sample structures fulfilled all stringent requirements on the cavities for atomic clocks, such as precise resonance frequency, quality factor, homogeneity and uniformity of the microwave field. Tests in an experimental atomic clock setup showed a fractional frequency stability of $2x10^{-13}$ at one second integration time, which is on the same level as today's best vapour-cell clocks using conventional cavities. A fully monolithic cavity was also designed and realized (Figure 1b), including a 3D-printed coupling loop that further simplifies the cavity assembly and improves reproducibility.

Accelerated aging tests over 800 thermal cycles up to 85°C were performed on test samples produced by SLA. No measurable degradation of RF performance or material integrity was observed, which shows the reliability of the SLA technique and constitutes a first step towards space qualification.

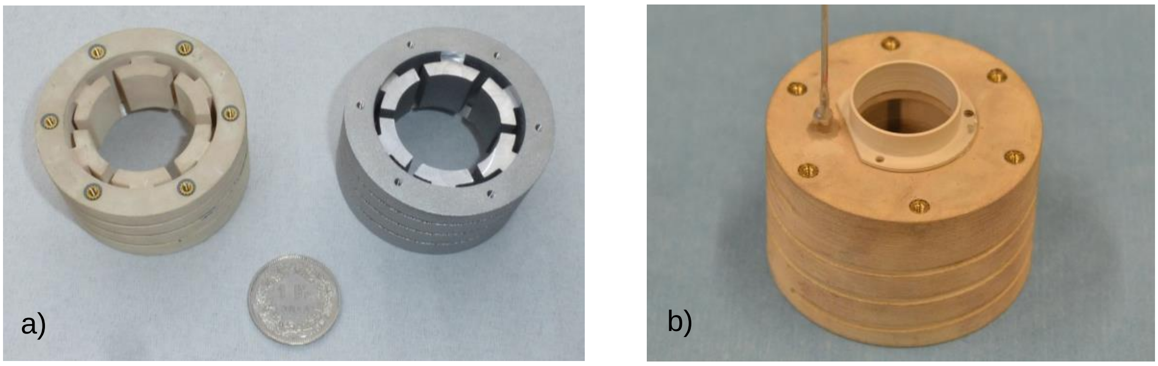

Figure 1: a) Cavity structures manufactured by SLA (left) and SLM (right). b) Fully monolithic cavity manufactured by SLA, including a coupling loop.

Conclusion:

The project has shown that 3D-printing by both SLA and SLM is appropriate for manufacturing complex microwave cavities with stringent dimension tolerances. The approach has the advantages of good reproducibility and strongly simplifies cavity assembly. In the case of SLA, around 30% weight reduction can be obtained.

Tests on clock system level demonstrate that the 3D-printed cavities perform on the same level as conventional ones, shown here for the highly demanding application in a high-performance vapour-cell atomic clock. The 3D-printing approach can also be applied to cavity designs for other clock types with different or relaxed requirements, thus opening a wide application potential in many types of atomic clocks.

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