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Thermal Stability Analysis of 3D Printed Resonators Using Novel Materials

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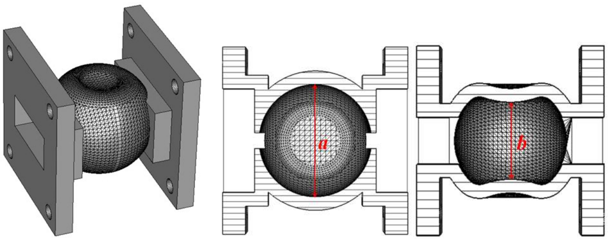
***Abstract* — This paper presents an investigation into the thermal stability of microwave cavity resonators using several novel alloy materials. Shaped spherical resonators are additively manufactured by Selective Laser Melting (SLM) technology from alloy powders. The manufacturing parameters of each sample is presented, and their thermal stability is experimentally characterized by measuring the RF performance under different temperatures. The Ti64, Zr702 and TNTZ samples show much improved thermal stability as compared with the common aluminium alloy used for space application. A detailed comparison between different samples in terms of their mechanical, thermal and RF performance is presented. This work introduces an expanded range of materials that may be used for microwave filters and opens opportunity for new temperature compensation techniques for high power filters.**

***Keywords* — filters, cavity, additive manufacturing, new materials.**

I. INTRODUCTION

High-power microwave filters are an important class of components in satellite payloads. They are mostly used in output multiplexers (OMUXs) or antenna feeds handling power levels beyond 100W per channel from L-band up to Ka-band [1], [2]. Above X-band, most of these filters are formed of hollow metal cavity resonators for their low loss requirement. In addition, thermal conduction and lightweight performance are required, making Aluminium the preferred building material. Temperature variation is mainly due to the in-orbit operation (typically 15-85°C for OMUX) and the self-heating from the high-power RF dissipation. Without any compensation mechanism, this temperature variation would cause thermal expansion/contraction of the metal cavity and resulting in a frequency displacement of the filters response. So, most of the high-power filters require temperature compensation mechanisms. Due to its narrow bandwidth and the need to reduce the guard bands (and hence maximise the overall available frequency range utilization while reducing as much as possible the interference to adjacent channels), the channel filters in OMUXs have particularly stringent requirement in terms of thermal stability. It requires either external temperature compensation structures [3] or the use of invar alloy [4] for its extremely low coefficient of temperature expansion (CTE) of 0.5 - 2 ppm/K. The external constraint structures often complicate the assembly and result in a bulkier structure, requiring in most cases complex tuning steps. As for invar, it is not an easy material to work with due to its high density and hardness in machining. Both approaches have been used in the industry for a very long time. This work aims to find new alternative temperature compensation solutions using new materials in combination of suitable manufacturing techniques.



(a) (b)

Figure 1. Dimpled spherical resonator. (a) Resonator geometries. (b) Cross-sections (a = 24.8 mm, b = 16.8 mm).

The advent of additive manufacturing technology (also known as 3D-printing) and the increasing adoption of this technology in space industry offer the opportunity to explore this technology together with new materials [5], [6]. 3D printing technology has several advantages: rapid prototyping of new concepts; unique capability of free-form fabrication of complex structures which are difficult or impossible for subtractive techniques; and the versatility of printing with novel materials or even multi-materials. Some tentative work has been reported previously [7], [8] on the thermal performance of 3D printed filters but focusing on polymer-based materials, which does not really address high-power applications.

In this paper, a detailed investigation into several promising alloy materials is presented. Manufacturing parameters of each material sample are discussed. Detailed material characterization and thermal-RF test at different temperatures are reported on a dimpled spherical resonator. Good correlation has been shown between the RF test results and the expected material properties. A comprehensive comparison is made.

II. STRUCTURE OF EXPERIMENTAL SAMPLES

Two types of 3D-printed samples are used in this paper to investigate the mechanical, thermal and RF properties of the different alloy materials. The regular samples are used for mechanical and CTE testing over a wider temperature range. The microwave resonator samples operating at 10 GHz are used to investigate the actual RF temperature stability over the temperature range from room temperature to around +150 °C. This temperature range is limited by the available testing setup.

The microwave resonator employed in this work is a dimpled spherical resonator which is designed for additive manufacture [9]. Fig. 1 presents its geometries. Different from a regular spherical resonator, the top and bottom of this spherical cavity are symmetrically squeezed to push the first higher order mode farther away from the dominant mode. Meanwhile, a higher unloaded quality factor (Q_u) than rectangular resonator can be achieved.

III. MATERIAL AND MANUFACTURE

A. Materials

Several promising metallic alloys are selected to manufacture the experimental resonators and regular samples, including invar alloy, Ti-6Al-4V alloy (Ti64), Ti-Nb-Ta-Zr beta-titanium alloy (TNTZ), Zr702, and the aluminium-copper alloy A20X. Among them, TNTZ and Zr702 are novel to the microwave industry. The A20X is used as the reference material, since its property is similar to the common aluminium alloy.

Invar alloy is a widely used low CTE material. However, the density of invar is high (8.1 g/cm^3) and the strength-to-density ratio is low. This leads to the high weight of components made from invar, which, together with the very limited thermal conductivity, limits its application especially in payload-sensitive applications. This material is also very hard to machine. So, free-forming additive manufacturing technique offers a high-potential alternative fabrication solution. Although SLM invar [10] has been well studied, there is little work on SLM invar filters reported in the open literature.

Ti64 is a commonly used high strength alloys with high strength-to-weight ratio, which means the components may be formed thin and light weight. Ti64 is also one of the most used materials in additive manufacturing. The CTE of Ti64 is 8.6 ppm/K, much lower than aluminium but higher than Invar. Its electrical conductivity is even poorer than invar.

TNTZ alloy was originally designed and mostly used for orthopaedic implants. It has similar strength and density to Ti64. Literature has shown this alloy promises a CTE as low as 2 ppm/K after special heat treatment [11], [12]. Zr702 is close to pure zirconium. It has similar properties as titanium in many ways. Its CTE is 34% lower than Ti64. One drawback of Zr is its relatively high density but its strength is like titanium.

A20X is a high strength Al-Cu alloys with TiB2 doping. The strength of A20X is about 400 MPa but the density is low, hence the components made from A20X can be light weight. However, the CTE of Al-Cu alloys is much higher than the others.

The general properties of these selected materials are summarised in Table 1. The data are mostly from the literature, which will provide a reference for comparison with the actual material characterization and RF experimental results in this paper.

Table 1. General properties of the selected materials

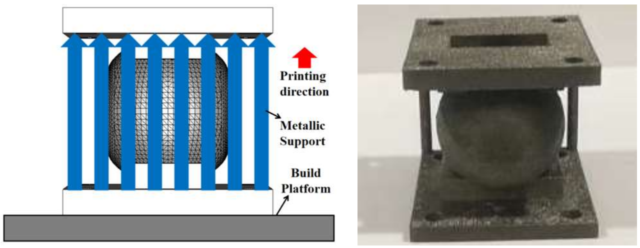
	Invar	**TNTZ**	**Zr702**	**Ti64**	**A20X**
Density (g/cm^3)	8.1	4.5-5	6.5	~4.4	2.85
Young's modulus (GPa)	140	36-52	95	110	75
Elongation (%)	45	10-20	32	5-18	>10
CTE (ppm/K)	0.5-2.0	-2.5 - +3.8	5.7	8.6	20.4
Thermal conductivity (W/m·K)	12-15	~7.8	22.6	6.7	175

B. Manufacturing techniques

All samples are additively manufactured using laser powder bed fusion (L-PBF) technique, also known as selective laser melting (SLM). Three different types of machines are used in this study. Table 2 summarizes the printers and the main processing parameters.

Table 2. Printing machines and processing parameters.

	Ti64	**Invar, TNTZ, Zr702**	**A20X**
Printer	RenAM 500 M	Concept Laser M2	SLM500HL
Layer thickness (μm)	30	30	30
Laser power (W)	200	400	360
Scan speed (mm/s)	1500	4000	1500
Hatch distance (mm)	0.105	0.45	0.15
Spot size (μm)	70-75	70-80	70-80



(a) (b)

Figure 2. (a) Diagram showing the printing direction. (b) Photo of the printed resonator sample with external supporting structures.

The printing direction is parallel to the longitude of the microwave resonator components as shown in Fig. 2. Samples were cut off from the substrate via EDM and the cut surface was mechanically ground. The post polishing was done by Sharmic vibration polishing machine with 3 mm size ceramic particle media. The standard polishing process takes 6 hours, and the samples are ultrasonic cleaned with ethanol for 10 min and dried in oven at 100°C for further testing. Our RF measurements are performed on as-printed samples. Figure 3 shows the pictures of the as-printed sample resonators from the five different alloy materials.

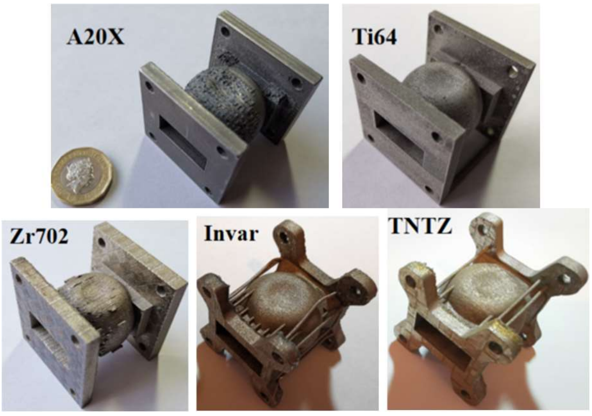


Figure 3. Photographs of the as-printed sample resonators.

IV. EXPERIMENTAL SETUP AND RESULTS

To accomplish the resonator-based thermal test, an experimental setup was built. It mainly contains four parts: heat source, thermal shielding and thermometer, a pair of thermal isolators, and RF measurement equipment. Fig. 4 presents the schematic diagram of the measurement setup.

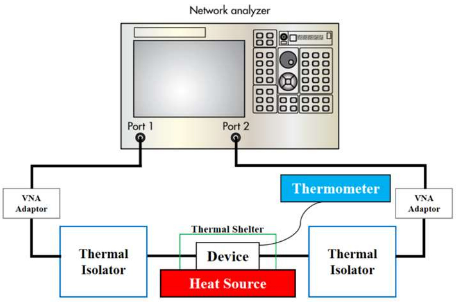
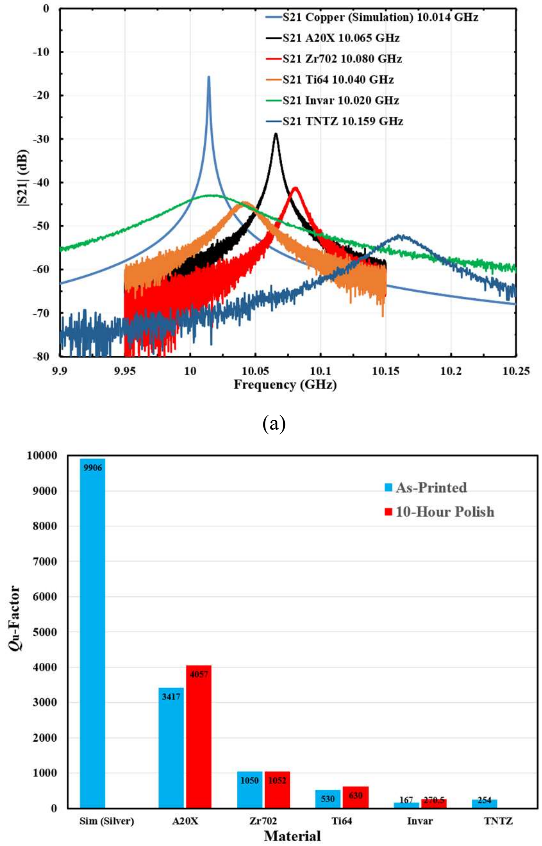


Figure 4. Schematic diagram of the thermal measurement setup

A Gallenhamp hot plate is employed here as heat source. The thermal shield is made up of a box covered by aluminium foil, while the real-time temperature is monitored by a multimeter (ATP MY-64) through a K-type thermocouple. The functionality of the thermal isolator is to separate the RF measurement equipment from the heat source [13]. Each thermal isolator is composed of two sections of X-band rectangular waveguide that are separated by a 1-2 mm air gap. To avoid the radiation from the gap, periodic bandgap structure is used between the two waveguide flanges. Agilent E8361C network analyser is used. Although the in-house built setup cannot match the accuracy of a commercial thermal chamber in temperature control, the results are adequately indicative of the thermal performance of the devices.

During the test, a set of transmission response at room temperature (around 20 °C) were first taken as a benchmark as shown in Fig. 5(a). This serves a first-order indication of the dimensional accuracy of the as-printed resonators. All samples have a slightly higher resonance frequency than expected by simulation. This could be partially alleviated by predesign compensation for the dimension. Fig. 7(b) compares the measured quality factors of the samples at room temperature where some samples have been polished. As can be observed, the low CTE materials generally have very low Q_u, which necessitate conductivity-enhancing coating in order to achieve the required RF performance. Polishing has shown some limited positive effect.



(a)

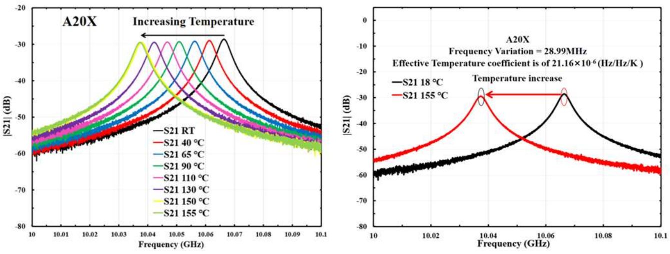
(b)

Figure 5. (a) Measured resonance curves at room temperature. (b) Comparison of the measured Q_u of the as-printed resonators.

Temperature was then raised up to around 160 °C at an interval of around 20 °C. The resonator's scattering coefficients were measured at each temperature after a stabilization time of 30 - 40 minutes. Fig. 6(a) shows the measured resonance curves as a function of temperature for the A20X sample, where the frequency shift is clear. Theoretically, the percentage frequency shift is approximately equal to the CTE times the temperature range. That is $\Delta f / f \approx -$ CTE × Temperature-range. However, the CTE of the bulk material is not identical to that of the resonator. We define the 'effective temperature coefficient' of the resonator as $d(\Delta f/f)/dT$. It has the same unit of ppm/K as the CTE of the materials. Shown in Fig. 6(b) is an example for A20X sample where the start and end temperature are used to extract the effective temperature coefficient. For comparison, Fig. 7 presents the measured resonance curves and calculated effective temperature coefficients of the other four resonator samples formed of lower CTE materials. The improvement in the thermal stability of the resonator is significant.

Table 3. Test result summary of as-printed resonator samples

Materials	**Literature**	**Flat Sample (As-printed)**	**10 GHz Resonator (As-printed)**	
	CTE (ppm/K)	CTE (ppm/K) @25-140°C	Freq. temp. coefficient (ppm/K), @20-150°C	Q_u @20°C
Invar	0.5-2	1.43	1.85	167
TNTZ	-2.5 - +3.8	8.26	7.68	254
Zr702	5.7	7.32	5.95	1050
Ti64	8.6	8.48	7.43	530
A20X	20.39	19.05	21.16	3417



(a) (b)

Figure 6. A20X resonator: (a) Measured resonance curves as a function of temperature; (b) Calculated effective temperature coefficient.

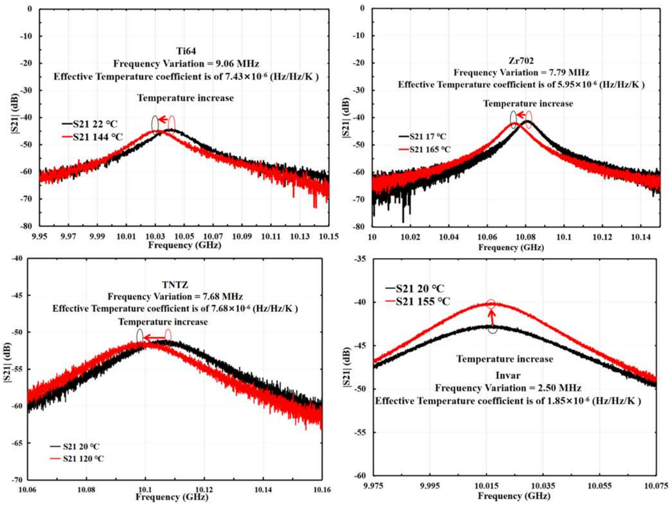


Figure 7. Resonance curves used to calculate the effective temperature coefficients for the as-printed sample resonators with low CTE materials.

Additionally, the CTE of the materials was measured by the TA Instruments TMA 2940 Thermo-Mechanical Analyzer, generally in accordance with BS ISO 11359-2:1999. Good correlation between the measured CTE of the materials and the measured effective temperature coefficient of the resonators has been shown in Table 3. However, the TNTZ samples show much higher CTE than the literature value [11]. It is known the CTE of TNTZ is highly dependent on the manufacture process and heat treatment.

V. CONCLUSION

This paper evaluated the thermal stability of microwave cavity resonators, additively manufactured using several alloy materials with low CTE. Ti64, Zr702 and TNTZ show much improved temperature stability compared with aluminum. Most temperature-dependent RF measurement results show good correlation with the expected CTE properties of the materials. The TNTZ sample did not reach the lowest CTE reported in the literature, which requires further investigation. The work also demonstrated the printability of monolithic and irregular shaped resonators using these new materials. This increases the range of materials that may be used for microwave filter and opens opportunity for new temperature compensation mechanism for high power filters. Future work is expected for the manufacturing of complex RF functions, making benefit of the selection of highly stable building materials. End-to-end manufacturing methods will be investigated considering, for example, the required metal coating for RF performance improvement.

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