A Novel Configuration for Microwave Resonator with Zero Temperature-Coefficient

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***Abstract*—We present a simple yet novel design of a cylindrical microwave resonator with a turnover in the frequency versus temperature response. The basis for the design is to compensate for the thermal changes in the radius and length of the cavity cylinder by using re-entrant end caps with a higher temperature coefficient of expansion than that of the cylinder. For the proper choice of inside cylinder diameter and length, one can achieve sufficient separation of the desired TE023 mode from competing modes, Q-factors approaching 59,000, and a turnover temperature at the desired frequency. Details of a X-band cavity using silver plated molybdenum for the cylinder and silver plated aluminum for the re-entrant end caps are presented**

I. INTRODUCTION

Figure 1 shows the schematic of a high performance X-band cavity stabilized oscillator investigated earlier at NIST [1]. This design was characterized by the use of a 2 W source, a high-Q Al air dielectric cavity, near critical input coupling and very loose output coupling. The use of near critical coupling helps reduce the added noise of the circulator and the mixer used in the frequency discriminator [1]. Figure 2 shows the phase noise achieved with this configuration. Detailed analysis showed that thermal fluctuations resulting in random walk frequency modulation ($L(f) \propto 1/f^4$) play a significant, if not dominant, role in the phase noise for offset frequencies less than roughly1000 Hz [1]. The way around this problem is either to provide tighter temperature control or to use a cavity with a very small temperature coefficient of resonator frequency. The thermal sensitivity of the Al cavity frequency was about 239 kHz/K. In the present work we present details of a new X-band microwave cavity design that exhibits a turnover in the frequency versus temperature at virtually any convenient temperature of choice, is all metal to help keep the thermal gradients at a minimum, and achieves an unloaded Q-factor over 58,000. This should allow one to operate at a temperature near the turnover and achieve a temperature coefficient of resonant frequency a factor of 1000 lower than the traditional all Al cavities used previously [1].

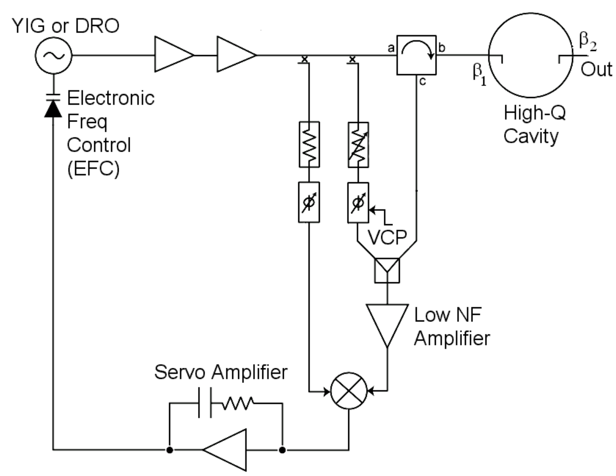

Fig. 1. Schematic of a high performance X-band cavity stabilized oscillator described in [1]

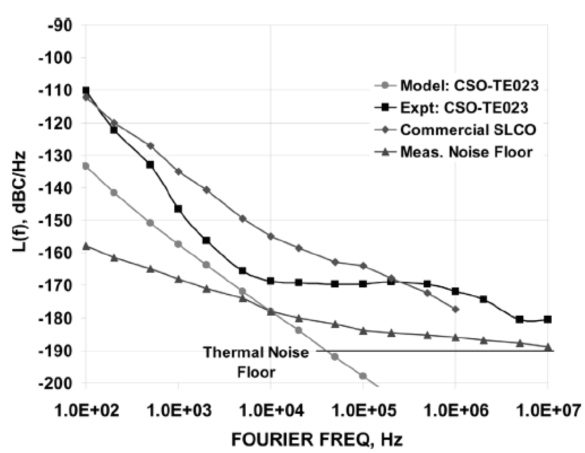

Fig. 2. Phase noise performance versus Fourier offset frequency for the aluminum cavity design detailed in [1]

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II. CAVITY DESIGN

The cavity configuration is shown schematically in Fig.3. Here the cavity cylinder is made up of a low Temperature Co-efficient of Expansion (TCE) metal, having a length of d_{cyl} and an inner diameter 2a. The end caps are made of Aluminum, each having a re-entrant section of length $d_r/2$. The resonant cavity thus formed is then defined by a diameter 2a and length d (= d_{cyl}-d_r)

For a specific case of higher order transverse electric (TE) mode of oscillations in a resonator, say TE023 the resonance frequency is given by

$$f_{res} = \frac{c}{2\pi}\sqrt{\left(\frac{7.016}{a}\right)^2 + \left(\frac{3\pi}{d}\right)^2} \tag{1}$$

To achieve $\frac{df_{res}}{dT} = 0$ we must have

$$\frac{dd}{dT} = -\left(\frac{1}{a}.\frac{da}{dT}\right).\left(\frac{7.016}{3\pi}.\frac{d}{a}\right)^2.d = TCE_{cyl}.\left(\frac{7.016}{3\pi}.\frac{d}{a}\right)^2.d \tag{2}$$

Noting that

$$\frac{dd}{dT} = \frac{dd_{cyl}}{dT} - \frac{d_r}{dT} = TCE_{cyl}.d_{cyl} - TCE_{ecap}.d_r, \tag{3}$$

we get

$$d_r = \frac{TCE_{cyl}}{\left(TCE_{ecap} - TCE_{cyl}\right)}.\left[1 + \left(\frac{7.016}{3\pi}.\frac{d}{a}\right)^2\right].d \tag{4}$$

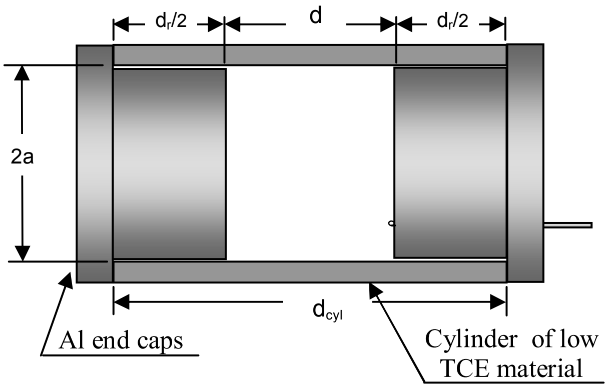

Fig. 3 Schematic of the compensated cavity

Thus for a chosen set of cavity dimensions, 2a and d, in order to resonate at a certain frequency f_{res}, one can compute d_r from eqn.(4) and hence d_{cyl} (= d + d_r). A noteworthy feature of the present design is that the re-entrant portions of the cavity end caps serve the dual purpose of providing temperature compensation by length reduction with temperature; as well as act as choke flanges to kill undesired modes of the cavity.

Fig. 4 shows a simulation of the resonance frequency of the TE023 mode in the above configuration. Around 25°C the temp-co is close to zero (~ 2 Hz/°C). Over the temperature range 10-40°C, the temp-co remains less than ±20 Hz/°C. This is more than three orders of magnitude smaller than the temp-co of an ordinary Aluminum cavity. In case of an actual fabrication we expect a certain level of degradation of the compensation due to finite machining tolerances of the various dimensions.

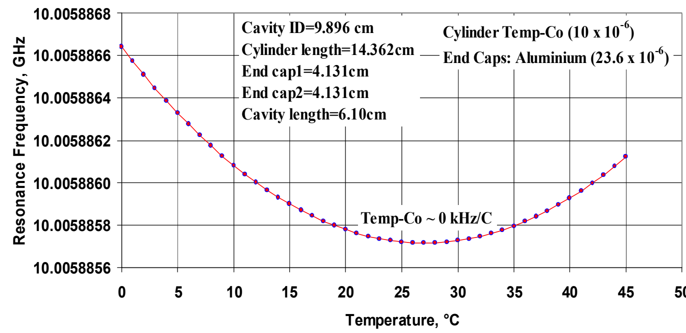

Fig. 4 . Theoretical computations of resonance freq vs temperature for a typical case.

III. EXPERIMENTAL RESULTS OF COMPENSATED CAVITY

Two cavities were fabricated in accordance with the general design concept of Fig.1. The cavity cylinder and the end caps were made out of Mo (temp. coefficient of expansion, TCE= 4.9×10^{-6}) and Al (TCE = 23.6×10^{-6}) respectively. The inside surfaces of the cavity were silver plated for high conductivity. The signals in and out of the cavity were coupled using small loop probes at the end of stainless steel jacketed co-axial cables. Initial measurements using a network analyzer were not very reproducible until isolators were placed on both the input and output cables to the cavity. The cavity insertion loss was typically set to – 37 dB to minimize the effects of the external circuit on the cavity frequency and Q-factor. Fig 5 shows the first cavity configuration. Note that the left end cap is slightly longer than the right one to allow trimming to adjust the temperature response. The final frequency adjustment will be done by trimming the cylinder length. Fig. 6 shows the frequency vs. temperature for this configuration. The measured Q-factor in this configuration was typically over 58,000. The cavity temp-co is about +13.1 kHz/C indicating that the cavity is slightly (5.5%) over compensated. Within the resolution of the data there is no evidence yet of curvature in the frequency versus temperature response

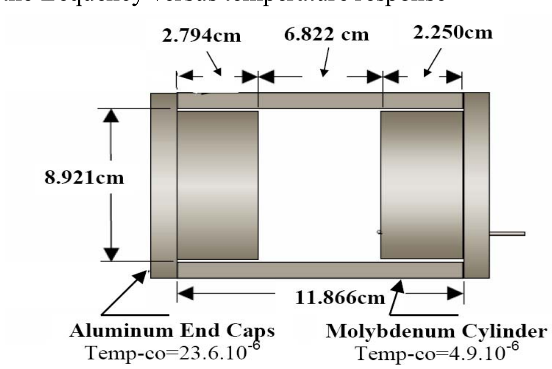

Fig. 5. First experimental cavity configuration

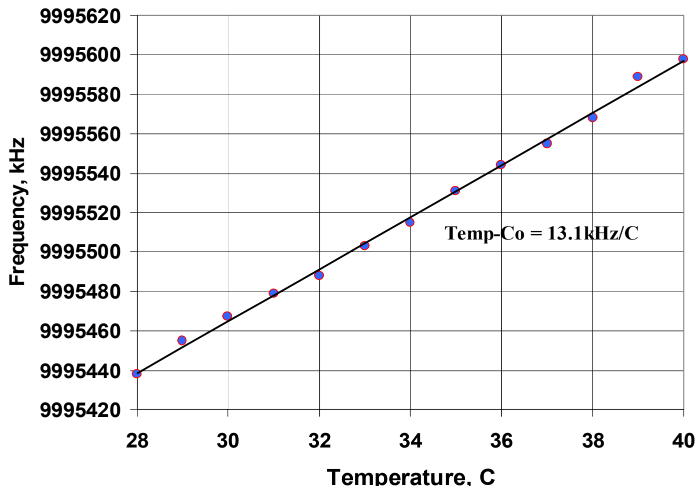

Fig. 6 Experimentally measured cavity frequency vs. temperature for the first experimental cavity.

Based on the data of Figure 6 the insertion length of the left end cap was replaced with one with a re-entrant length of 2.250 cm resulting in the frequency versus temperature response of – 4.5 kHz/C as shown Fig. 7. The cavity is now 2% under compensated and again to within the scatter in the data, there is little indication of curvature in the response. The calculated frequencies and temperature response are consistent with the relative TCEs of the end cap to cylinder to be 23.9 x 10^{-6}/C to 4.6 x 10^{-6}/C. The data of Figs. 6 and 7 and equations (1-4) are consistent with a change in cavity frequency temp-co of about 3.5 kHz/C per mm change in the insertion length of the end caps. An increase in insertion length of 0.014 cm should produce a near zero temp-co for the cavity resonance in the region of 30C.

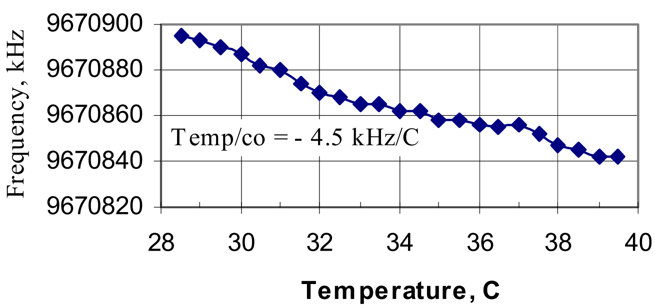

Fig. 7 Experimental data of resonance frequency vs temperature of the second experimental cavity

Coarse adjustment of the cavity frequency is obtained by trimming the cylinder length, while fine adjustment is obtained by use of a silver plated stub in the center of the input end cap. Figure 8 shows the cavity tuning vs. insertion length of the stub. The effect on cavity Q-factor was found to be less than 1% for tuning offset less than 1.5 MHz. We have not yet measured the effect of offset tuning on cavity frequency temp-co.

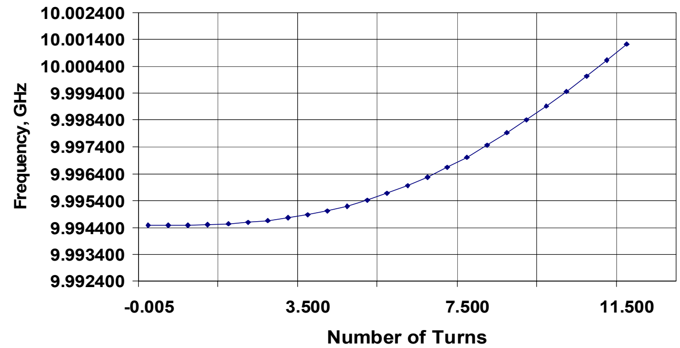

Fig. 8 Experimental data of resonance frequency vs. the number of turns of the central tuning stub

IV. Results and Discussion

We have presented a novel compensated cavity design that appears capable of achieving a turnover in the frequency vs. temperature response at room temperature. Operation near this turnover point should produce temperature coefficients that are less than 200 Hz/C or at least 1000 times smaller than traditional Al cavities operating on the same TE023 mode. This re-entrant cavity design naturally provides mode trapping for other modes. The unloaded Q-factors achieved were over 58,000, which is similar to that obtained with the silver plated all Al cavity used in [1]. With this new cavity design we expect to obtain significant reduction in the random walk FM noise (f^{-4} PM noise) observed in the work of [1].

Acknowledgment

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References

1. A. Sen Gupta, D.A. Howe, C. W. Nelson, A. Hati, F.L. Walls and J.F. Garcia Nava. "High-Spectral-Purity Microwave Oscillator: Design Using Conventional Air-Dielectric Cavity", IEEE Trans. on UFFC, Vol 51, No 10, pp 1225 – 1231, Oct 2004