The Temperature Compensation for TE011 Mode Resonator with Bimetal Material

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Abstract **─** This paper proposes a temperature compensation design for TE011 mode resonator based on multiphysics analysis. The relationship between structure and electrical performance of circular waveguide resonator is specifically analyzed. Furthermore, a novel temperature compensation structure with bimetal material is proposed by using multiphysics analysis. The proposed TE011 mode resonator is fabricated and tested to verify the design method. The temperature drift coefficient of the compensated TE011 mode resonator can be dramatically reduced from 21.387 ppm/°C to 0.93ppm/°C.

Index Terms **─** Bimetal material, multiphysics analysis, temperature compensation, TE011 mode resonator.

I. INTRODUCTION

Microwave waveguide cavity devices are widely applied in communication systems, especially in satellite communication systems and 5G millimeter wave communication systems. The frequency response of the device is usually affected by temperature, due to thermal expansion and contraction of metal. It is especially serious in narrowband or high-power applications. Therefore, temperature compensation design is very important to ensure the stable electrical performance of waveguide devices [1].

Conventionally, materials with low coefficient of thermal expansion (CTE) are usually applied in cavity structures to achieve stable frequency response, such as Invar [2]. However, Invar's high density, poor thermal conductivity and high hardness limit its application. In [3], Shape Memory Alloys (SMAs) is used in temperature-compensated cavity resonators. But accurate analysis and design for temperature compensation is difficult to achieve, due to the nonlinear characteristics of SMA parameters. Dielectric resonators are also widely used to obtain temperature stability [4-5] in applications other than high power conditions. In addition, dielectric sphere for temperature compensation is proposed in [6], which introduced a perturbation in electromagnetic field to eliminate temperature drift. [7-9] introduced bimetal material to the tuning screw, which shows good compensated results by controlling the size of the tuning screw. In [9], we first proposed the method of temperature compensation based on multiphysics simulation. It introduced bimetal material to the tuning screw in the waveguide filter. Compared with other methods, the use of bimetal can realize flexible temperature compensation structures with low cost and easy processing. However, bimetal loaded tuning screws reduced structural stability and increased assembly complexity. Moreover, TE011 mode resonator plays an important role in communication systems due to its high Q value [10-13].

This paper proposes a temperature compensated TE011 mode resonator with bimetal material. The relationship between the structure and electrical performance of TE011 mode resonator is completely analyzed in detail. With the numerical solution, the whole design can be implemented by using multiphysics analysis. The designed temperature compensated TE011 mode resonator is fabricated and tested from -20°C to 80°C. The simulated and measured results suggest it has excellent temperature drift coefficient as 0.93ppm/°C.

II. ANALYSIS AND DESIGN

As well known, TE011 mode resonator has no longitudinal current. And when transmission power is constant, the cavity power loss decreases as the increasing of frequency. It has a high Q value and is

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widely used in high power applications. To achieve precise temperature compensation design, deformation analysis of the TE011 mode resonator is needed.

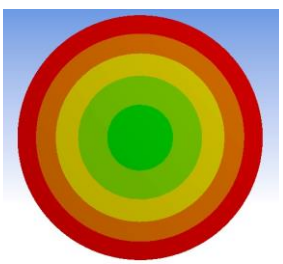
A. The deformation analysis of TE011 mode resonator

The cavity deformation of TE011 mode resonator caused by temperature change can be equivalent to the metal cylindrical model. Figure 1 is the equivalent deformation model of aluminum at 80°C.

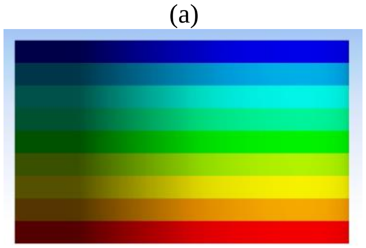
Figure 1 (a) represents the circumferential deformation of the equivalent deformation model and Fig. 1 (b) is the axial deformation. The green part in the Fig. 1 represents the smallest deformation, and red represents the largest deformation. When the temperature changes, the resonator will not only have a circumferential deformation [12], but also an axial deformation. Both affect the electrical performance. The relationship between frequency response and deformation is derived as follows. The frequency of TE011 mode resonator [14] can be expressed as (1):

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}. \tag{1}$$

Where *a* is the radius of the circular cavity and *d* is the height of circular cavity (at normal temperature: 20°C). p'_{nm} is the root of Bessel (*n*, *m* and *l* are the number of standing waves of extension radius, radius and axial).



(a)



(b)

Fig. 1. The circumferential and axial deformation of the equivalent model: (a) the circumferential deformation, and (b) the axial deformation.

Due to the deformation of metal is linear, the deformation of cavity can be shown as (2). Where a' and d' are cavity radius and height at changed temperature. Δa and Δd are the difference [15]:

$$\begin{cases} a' = a + \Delta a \\ d' = d + \Delta d \end{cases}. \tag{2}$$

After deformation, the frequency response of the TE011 mode resonator can be obtained as (3):

$$f'_{nml} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p'_{nm}}{a'}\right)^2 + \left(\frac{l\pi}{d'}\right)^2}. \tag{3}$$

The change of frequency caused by temperature is:

$$\Delta f = f'_{nml} - f_{nml}. \tag{4}$$

In order to simplify analysis, $f'_{nml} + f_{nml}$ is introduced as shown in (5):

$$\Delta f\left(f'_{nml} + f_{nml}\right) = \left(\frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}}\right)^2 \cdot \left(\left(\frac{p'_{nm}}{a'}\right)^2 + \left(\frac{l\pi}{d'}\right)^2 - \left(\frac{p'_{nm}}{a}\right)^2 - \left(\frac{l\pi}{d}\right)^2\right). \tag{5}$$

Therefore, when set $\Delta f = 0$, the frequency shift caused by circumferential deformation can be compensated as shown in (6):

$$\left(\frac{p'_{nm}}{a}\right)^2 \frac{2a\Delta a}{(a+\Delta a)^2} + \left(\frac{l\pi}{d}\right)^2 \frac{2d\Delta d}{(d+\Delta d)^2} = 0. \tag{6}$$

That is,

$$|\Delta d| = \left(\frac{p'_{nm}}{l\pi}\right)^2 \left(\frac{d}{a}\right)^3 \Delta a. \tag{7}$$

It can be seen that circumferential deformation can be compensated, when Δa is proportional to Δd. Thus, it can be compensated by controlling the height of the cavity.

Furthermore, the axial expansion deformation Δd_1 can be calculated as:

$$\Delta d_1 = d \cdot (T - 20^\circ C) \cdot \alpha. \tag{8}$$

Where *d* is the height of cavity and *T* is ambient temperature. α is the coefficient of thermal expansion. Obviously, the axial deformation can be directly compensated by changing the height of the cavity. That is, the temperature drift of TE011 mode resonator can be fully compensated by controlling the height of the cavity. Therefore, it is essential to propose a structure that can control the height of the cavity. In this work, a loading structure is proposed to achieve the temperature compensation, which will be introduced in detail as follows.

B. Temperature compensation design based on bimetal material

To achieve the temperature compensation, the height change of the resonator should be controlled as ΔD:

$$\Delta D = \left(\frac{p'_{nm}}{l\pi}\right)^2 \left(\frac{d}{a}\right)^3 \Delta a + L \cdot (T - 20^\circ C) \cdot \alpha. \tag{9}$$

The first important part of the loading structure is a control structure. Bimetal material is introduced to realize the control structure. Bimetal material is combined of two layers of metals with different thermal expansion coefficients. The bend of bimetal is caused by the different CTE of each layer. As shown in Fig. 2, in bimetal, the layer with a relatively large coefficient of thermal expansion is called active layer (A) and the relatively small layer is called passive layer (B). Due to its linear characteristic at temperature, the deformation of bimetal can be used to control the height of the cavity.

Based on the deformation of bimetal, the loading structure is proposed as shown in Fig. 3. It includes a control structure and a ceiling part. The double-ended fixed structure of the bimetal ensures that the deformation can only produce in the axial direction. Since the deformation of the bimetal controls the height of the ceiling, ΔD is applied to calculation the size of bimetal under certain boundary conditions.

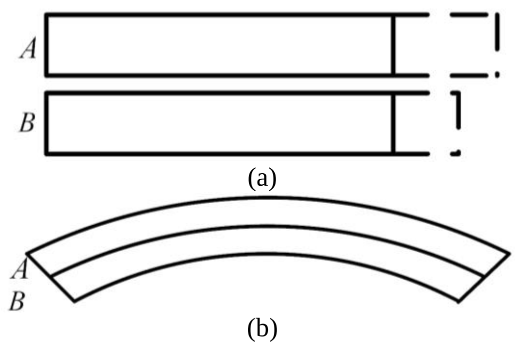


Fig. 2. The deformation of bimetal: (a) the deformation of the passive layer (A) and the active layer (B), respectively, and (b) the whole deformation of the bimetal.

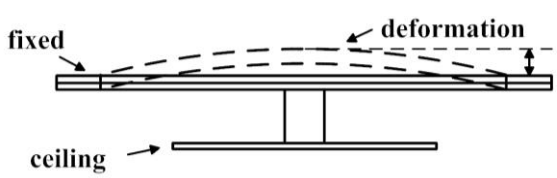


Fig. 3. The deformation of bimetal when two-ended fixed.

III. THE TEMPERATURE COMPENSATION OF TE011 MODE RESONATOR

As shown in Fig. 4, the relationship among electromagnetic, thermal and structural stress field can be obtained with multiphysics analysis [16]. ① represents the influence of electromagnetic field input power on the temperature and ② is the effect of the temperature field directly act on the electrical performance of the filter. The heat loss caused by the input power and the ambient temperature acts through ③ on the structural stress field. Structural deformation ⑤ caused by the temperature change will affect the frequency response of the filter. The environmental load and structural parameters act on the structural stress field through ④ and then affect the electromagnetic fields through the ⑤.

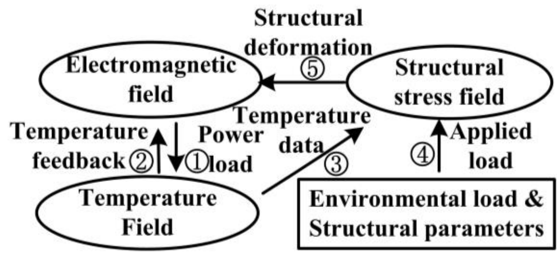


Fig. 4. The coupling relationship among multiphysics.

The final design of TE011 mode resonator is shown in Fig. 5. When the temperature changes, the center of bimetal structure will generate the biggest deformation and control the height of ceiling in the vertical direction to realize the temperature compensation. Symmetrically slots are added on both sides of bimetal to ensure the theoretical temperature compensated value.

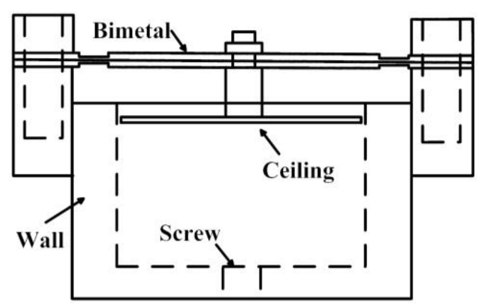
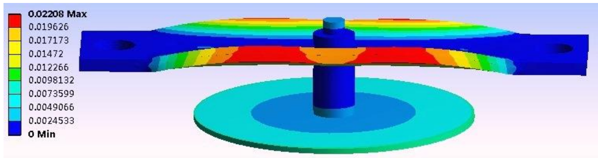
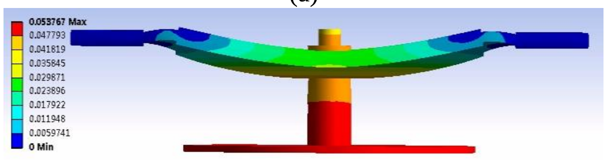


Fig. 5. The TE011 mode cavity resonator.

First, design a resonator that meets the electrical performance requirements. Then the deformation caused by temperature can be analyzed in static structural module of Ansys workbench. Finally, electrical analysis of the deformation structure is carried out with the updated grid data from structural stress field. Figure 6 shows the deformation comparison of the loading structure. As shown in Fig. 6, using slotted double-ended fixed structure can obtain a larger deformation range. When the center deformation of bimetal is equal to the ΔD, the structural size can be obtained.



(a)



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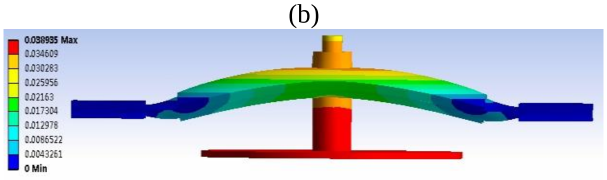


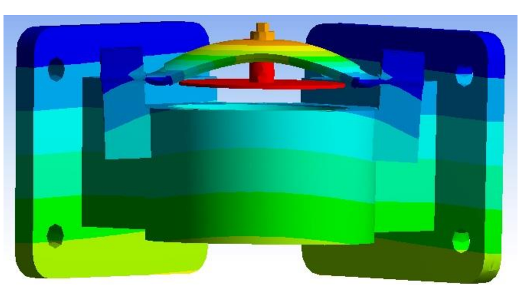
(c)

Fig. 6. The deformation of temperature compensated structure with bimetal: (a) double-ended fixed structure, (b) slotted double-ended fixed structure at 80°C, and (c) slotted double-ended fixed structure at -20°C.

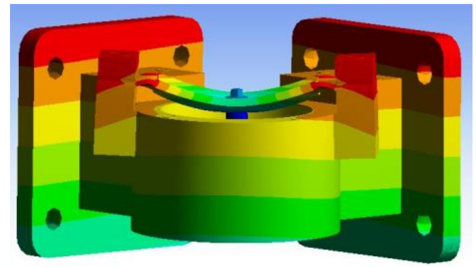
The deformation of the ceiling is mainly concerned since the height directly affects the cavity frequency. In Fig. 6 (a), the maximum displacement of ceiling is 0.0074mm under 80°C. However, in Figs. 6 (b) and (c), the maximum displacement of ceiling is 0.0537mm under 80°C and 0.0389mm under -20°C. The movement (initial values) of the ceiling achieves the theoretical values. The size of bimetal can be obtained.

Figure 7 shows the final temperature compensation design for TE011 mode resonator at -20°C and 80°C. When the temperature drops, the height (final values) of the ceiling will be increased, vice versa.

Take a TE011 mode resonator operating at 21.5 GHz as an example. Figure 8 is the frequency response of the TE011 mode resonator. In Fig. 8 (a), without temperature compensation, the frequency response offsets 46 MHz from -20°C to 80°C. The temperature drift coefficient is 21.387ppm/°C. As shown in Fig. 8 (b), with the proposed design, the frequency drifts only 1 MHz. And its temperature drift coefficient is dramatically reduced to 0.465ppm/°C.

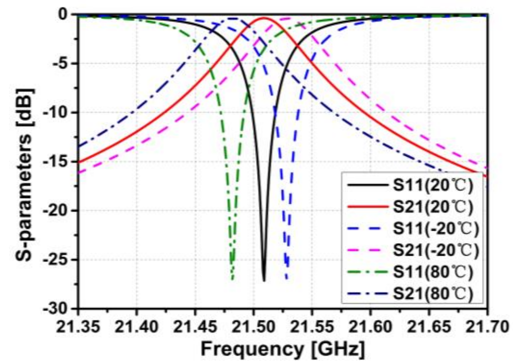


(a)

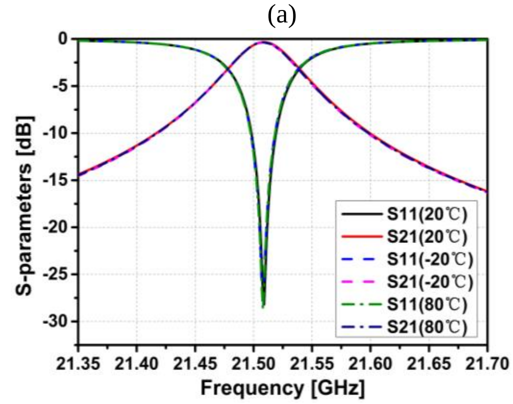


(b)

Fig. 7. The temperature compensated TE011 mode resonator: (a) the deformation at -20°C, and (b) the deformation at 80°C.



(a)



(b)

Fig. 8. The frequency response of TE011 mode resonator: (a) without temperature compensation, and (b) the proposed design.

The simulation results show the efficiency of the method and implement high thermal stability. The difference between the theoretical temperature compensated values and final values is shown in Table 1. Mainly due to some higher order component in (9) is neglected to get the theoretical values.

Table 1: Temperature compensated values (μm)

Temperature (°C)	-20	0	40	60	80
Final Values	36.7	19.2	15.7	33.2	52.3
Theoretical Values	38.8	20	16.4	35	53.4
Difference	2.1	0. 8	0. 7	1.8	1.1

IV. EXPERIMENT

The photograph of the temperature compensated TE011 mode resonator is shown in Fig. 9. Testing in a thermostat and the frequency response is given in Fig. 10. In the uncompensated structure, the frequency drift of TE011 mode resonator is 46 MHz from -20°C to 80°C. The temperature drift coefficient is 21.378ppm/°C. The frequency drift of proposed design is 2 MHz at -20°C to 80°C. The temperature drift coefficient is 0.93ppm/°C.

Fig. 9. The photograph of the temperature compensated TE011 mode resonator.

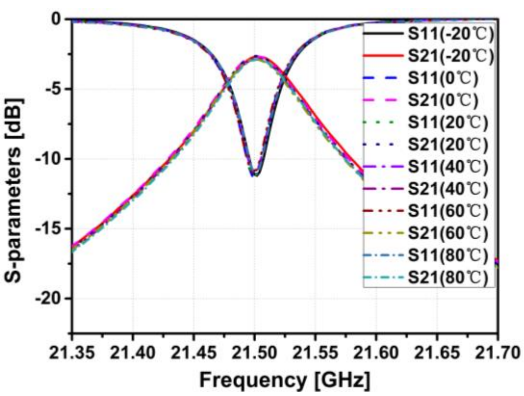


Fig. 10. The measured results of the temperature compensation TE011 mode resonator from -20 to 80°C.

The simulation results are consistent with the measured results, which verified the design. The proposed temperature compensated TE011 mode resonator can be easily extended to the filter temperature compensation easily.

A comparison with other reported works is given in Table 2. This work takes into account a wider range of application temperatures. As it is shown, with the proposed loading structure in this work, the temperature drift coefficient of the resonator can be dramatically reduced to 0.93ppm/°C. The method makes it easier for assembly and application.

Table 2: Comparison of the proposed temperature design

Refs.	**Frequency (GHz)**	**Temperature Range (°C)**	**Temperature Drift Coefficient**
[12]	12	20~100	1.56 ppm/°C
[13]	12.2	24~84	2.3 ppm/°C
This work	21.5	-20~80	0.93ppm/°C

V. CONCLUSION

This work proposes compensation for TE011 mode resonator using bimetal material is proposed with the multiphysics analysis. The relationship between the structure and electrical performance of TE011 mode resonator is completely analyzed. The modeling method is presented in detail with the numerical solution. The simulation and measure results confirm the effectiveness of the proposed design method.

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