Journal of Electroceramics, 15, 237–241, 2005

Dielectric Properties of Yttrium Vanadate Crystals from 15 K to 295 K

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Submitted March 31, 2005 ; Revised May 11, 2005; Accepted June 27, 2005

Abstract. Yttrium Vanadate (YVO_4) is a birefringent crystal, which has similar dielectric constant as that of Sapphire. In this paper we have reported the measurement of the real part of permittivity and loss tangent of YVO_4 crystal in the temperature range 15–295 K at a frequency of 16.3 GHz. We have used the dielectric post resonator technique for the microwave characterisation of the YVO_4 dielectric rod. The multifrequency Transmission Mode Q-Factor (TMQF) technique has been used for data processing and hence precise values of permittivity and loss tangent are achieved. Easily machineable YVO_4 is characterized by low losses at microwave frequencies. At temperature of 15 K and frequency of 16.3 GHz the permittivity was 9.23 and loss tangent was 2×10^{-5}. YVO_4 is identified as a potential candidate to replace expensive Sapphire in many microwave applications.

Keywords: Dielectric properties, YVO_4

1. Introduction

Yttrium Vanadate (YVO_4) is a birefringent crystal used as optical components such as fibre optical isolators and circulators, beam displacers and other polarizing optics [1–3]. The crystal growth and fabrication of YVO_4 are much easier than the similar birefringent crystals. Table 1 shows the comparison of four birefringent crystals such as YVO_4, TiO_2, Calcite and Lithium Niobate [1–3]. Compared to Calcite, YVO_4 has better temperature stability and physical and mechanical properties [3]. for calcite it is difficult to achieve high optical quality because of its low susceptibility to moisture and low hardness. In contrast to Rutile (TiO_2), which exhibits high hardness, YVO_4 is easier to be handled for optical surface processing that greatly reduces cost of fabrication, especially for batch production [1–3]. Even though $LiNbO_3$ and YVO_4 have similar mechanical and physical properties, YVO_4 has more than three times larger birefringence, which makes allows for more compact circuit design [3] and as a result miniaturisation of the device. YVO_4 exhibits attractive characteristics and hence it is considered as a potential substitute for other birefringent crystals.

The characteristics of YVO_4 at optical frequencies are well studied [1–3]. Other than the permittivity and loss tangent data published by our group for the temperature range 15 K–80 K [4] there is hardly any data available at microwave frequencies. Our previous study shows similarity in permittivity values between YVO_4 and Sapphire crystals. In this paper we have studied the variation in resonant frequency, permittivity and loss tangent with temperature using a $TE_{01\delta}$ mode dielectric post resonator. The dielectric post resonator [5] and Hakki-Coleman type dielectric resonators [6, 7] are typically used for the microwave characterisation of bulk dielectric materials.

2. Measurements of Microwave Properties of YVO_4

The schematic diagram of the dielectric post resonator is shown in Fig. 1. The YVO_4 crystal of height 3.09 mm and diameter 5 mm is grown by Czochralski method [8]. The measurement system we used for microwave characterisation of the YVO_4 sample consists of Network Analyser (HP 8722C), closed cycle refrigerator

Table 1. Comparison of properties of birefringent crystals.

	YVO_4	TiO_2	$CaCO_3$	$LiNbO_3$
Thermal Expansion (/C^o)				
c-axis	11.4×10^{-6}	9.2×10^{-6}	26.3×10^{-6}	16.7×10^{-6}
a-axis	4.4×10^{-6}	7.1×10^{-6}	5.4×10^{-6}	2×10^{-6}
Refractive Index				
n_o	1.9447 (at 1550 nm)	2.454 (at 1530 nm)	1.6346 (at 1497 nm)	2.2151 (at 1440 nm)
n_e	2.1486 (at 1550 nm)	2.710 (at 1530 nm)	1.4774 (at 1497 nm)	2.1413 (at 1440 nm)
Birefringence (n_e-n_o)	0.2039 (at 1550 nm)	0.256 (at 1530 nm)	−0.1572 (at 1497 nm)	−0.0738 (at 1440 nm)
Mohs Hardness	5	6.5	3	5
Deliquescence	None	None	Weak	None
Transparency range	0.4–5 μg	0.4–5 μm	0.35–2.3 μm	0.4–5 μm

(APD DE-204), temperature controller (LTC-10), vacuum Dewar, a PC and a $TE_{01\delta}$ mode post dielectric resonator.

The resonator containing the YVO_4 sample was cooled from room temperature to approximately 14 K. Using the Network Analyser the TE_{011} mode is identified at frequency of 16.3 GHz. The S_{21}, S_{11} and S_{22} parameters data sets around the resonance were measured at temperature of 15 K. Using the Transmission Mode Q-Factor (TMQF) technique [9] the measured data has been processed to remove all the parasitic losses occurred during the S-parameter measurement. The coupling coefficients (k_1 and k_2) were calculated from the S_{11} and S_{22} data sets using [10]:

$$k_1 = \frac{1 - |S_{11}|}{|S_{11}| - |S_{22}|} \tag{1}$$

and

$$k_2 = \frac{1 - |S_{22}|}{|S_{11}| - |S_{22}|} \tag{2}$$

In order to calculate the unloaded Q-factor precisely, the influence of the coupling coefficients were accounted in the calculation [10]:

$$Q_0 = Q_L(1 + k_1 + k_2) \tag{3}$$

where Q_L is the loaded Q-factor. For higher temperatures only S_{21} was measured and the unloaded Q-factor was calculated using a simplified TMQF method [11]. The simplified TMQF method calculates the coupling coefficient of both ports at each measurement temperature and hence the accurate unloaded Q-factor. The perpendicular component of the real part of relative permittivity and loss tangent is calculated from the resonant frequency and unloaded Q-factor respectively using the software [12].

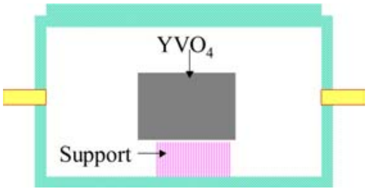

Fig. 1. The schematic diagram of YVO_4 dielectric post resonator.

3. Results and Discussion

Figure 2 shows the variation of resonant frequency with temperature. When the temperature increases from 15 K to 295 K resonant frequency shifts by 82 MHz.

The stability of a circuit or device with variations in the environment temperature depends on the change in frequency, permittivity and dimensions with temperature. The temperature coefficient of resonant frequency (τ_f) of the dielectric resonator, temperature coefficient of permittivity (τ_ε) of the material and the linear expansion coefficient (α) of the dielectric material can be related using the equation [13]:

$$\tau_f = A_\varepsilon \tau_\varepsilon + A_d \alpha + \tau C_x \tag{4}$$

where:

$$A_\varepsilon = \frac{\varepsilon_r}{f_0} \frac{\Delta f_0}{\Delta \varepsilon_r}, \tag{5}$$

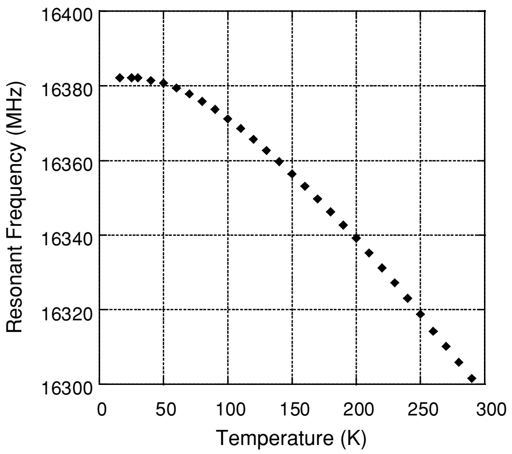

Fig. 2. The resonant frequency of the $TE_{01\delta}$ Mode resonator as a function of temperature.

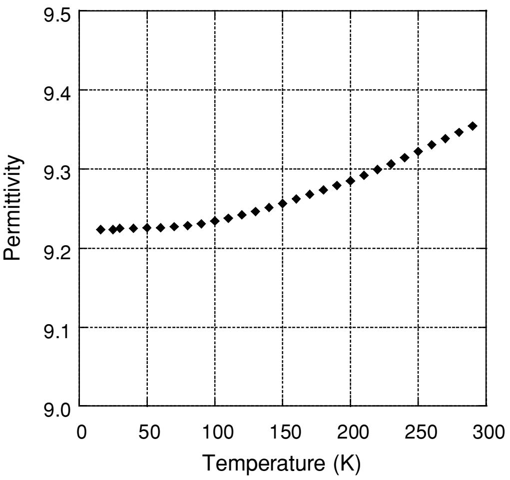

Fig. 4. The permittivity of YVO_4 crystal at 16.3 GHz as a function of temperature.

$$A_d = \frac{D}{f_0}\frac{\Delta f_0}{\Delta D} + \frac{L}{f_0}\frac{\Delta f_0}{\Delta L} \tag{6}$$

and τC_x describes temperature dependent properties of a Copper cavity. It is possible to neglect variations in cavity dimensions with temperature since it is very small. Therefore τC_x can be considered '0'. Theoretical analysis can be used for estimating the values of A_ε and A_d of a resonant structure. For a Hakki-Coleman type dielectric resonator A_ε and A_d are approximately -0.5 and 1.0 respectively [13].

The τ_f has been calculated from the measured resonant frequency of the dielectric resonator loaded with YVO_4 using the equation:

$$\tau_f = \frac{f_0 - f_{0T}}{f_0}\frac{10^6}{\Delta T} \tag{7}$$

where f_0 and f_{oT} are the resonant frequency at room temperature and at temperature T respectively.

The calculated τ_f from the measured $f_0$is shown in Fig. 3 as a function of temperature. The perpendicular component of real part of permittivity is calculated

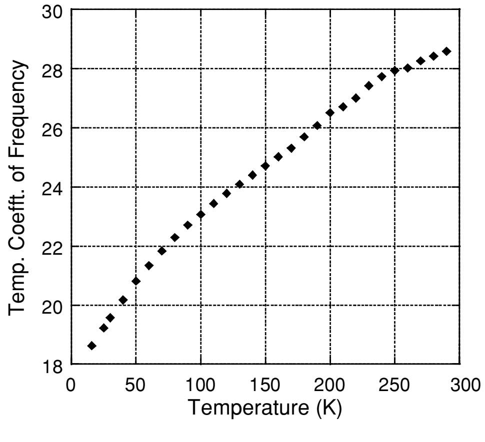

Fig. 3. Temperature coefficient of frequency of YVO_4 crystal.

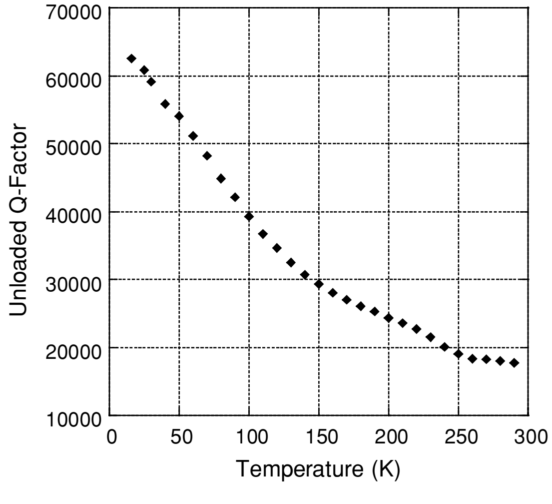

Fig. 5. The unloaded Q-factor of the $TE_{01\delta}$ Mode resonator as a function of temperature.

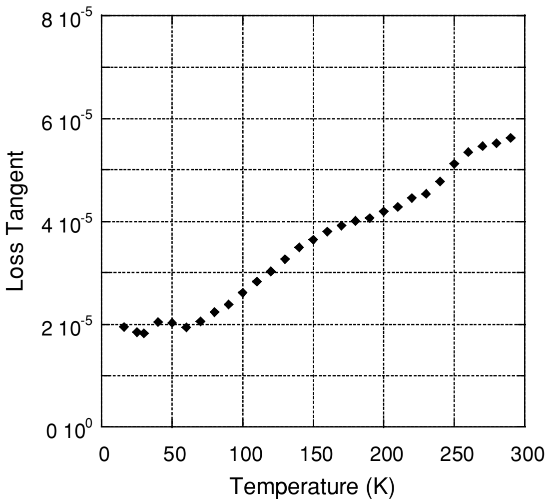

Fig. 6. The loss tangent of YVO_4 crystal at 16.3 GHz as a function of temperature.

using the f_0 data and is shown in Fig. 4. The coefficient of thermal expansion is not accounted in the calculation of ε_r. It is anticipated that the ε_r will be a maximum of 1% less than the values shown in Fig. 4 if the thermal expansion is accounted. The real part of permittivity increases by 0.13 in the temperature range 15–295 K. The total increase in ε_r is less than 1.5%. Therefore devices and circuits made using the YVO_4 will be good for stable performance under the varying temperatures.

Figure 5 shows the calculated unloaded Q factor as a function of temperature. The loss tangent of the YVO_4 crystal is calculated from the measured unloaded Q-factor and is represented in Fig. 6 at a frequency of 16.3 GHz. The loss tangent varies between 2×10^{-5} to 6×10^{-5}. Typically Engineers use the product of unloaded Q-factor and the resonant frequency of the resonator as a standard to choose a material for a given application. The variation of $Q_0 \times f_0$ as a function of temperature is graphically represented in Fig. 7.

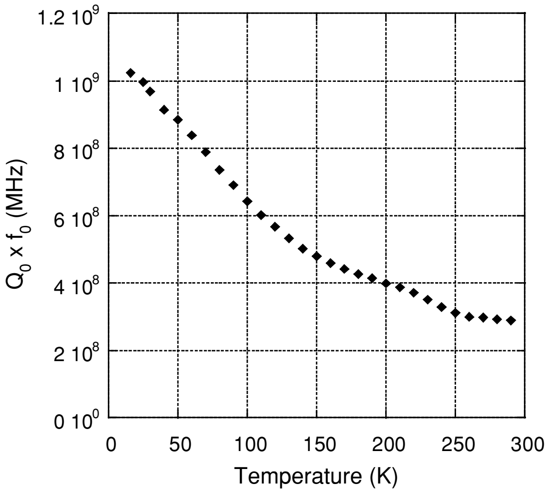

Fig. 7. The dielectric factor of YVO_4.

4. Conclusions

An yttrium vanadate crystal is characterised at microwave frequencies using a $TE_{01\delta}$ mode dielectric post resonator. The temperature dependence of frequency, permittivity and loss tangent of YVO_4 is studied at frequency of 16.3 GHz. The total shift in the resonant frequency in the temperature range 15 K to 295 K was 0.5%. The perpendicular component of the real part of permittivity of YVO_4 at frequency of 16.3 GHz increases from 9.22 to 9.35 (1.4%) when the temperature increases from 15–295 K. This shows that the temperature coefficient of permittivity will be small. The real part of the permittivity of YVO_4 is very similar to that of sapphire. The hardness of YVO_4 is much less than that of sapphire, which makes the machining of the material easier. The loss tangent varies between 2×10^{-5} to 6×10^{-5} in the temperature range 15–295 K. The low loss and low temperature coefficient of permittivity makes YVO_4 a promising material in many microwave applications.

Acknowledgments

The authors are grateful to the financial support provided under the JCU ARC Discovery Project 0449996. The first author also acknowledges the Australian Research Fellowship.

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