微波介電材料及其應用

Microwave Dielectric Materials and its Applications

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TOPICS

Introduction
• Background
• Motivation

Theory and Experimental
• $\text{AB}_2\text{O}_6$ Microwave Dielectric Ceramics
• Planar Filters

$\text{AB}_2\text{O}_6$ Microwave Dielectric Ceramics
• $\text{Zn(TaNb)}_2\text{O}_6$ Ceramics
• $\text{Mg(TaNb)}_2\text{O}_6$ Ceramics
• Discussion

Planar Filters
• Wide-Band/Dual-Band Filters
• Tri-band/Tetra-Band Filters
• Discussion

Conclusions and Future Works
In recent years, microwave dielectric materials have attracted great attention due to their better microwave dielectric characteristics than general microwave substrates, including high dielectric constant ($\varepsilon_r$), high quality factor at microwave frequency ($Q\times f$).

The requirements of the microwave dielectric resonators are:

- High dielectric constant ($\varepsilon_r$).
  - For miniaturization
- High quality factor at microwave frequency ($Q\times f$).
  - For reduction of the loss and performance improvement
- Near-zero temperature coefficient of resonant frequency ($\tau_f$).
  - For stability of the resonant frequency
### General Microwave Device Substrates

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Dielectric Constant</th>
<th>Loss Tangent</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4</td>
<td>4.4</td>
<td>0.02</td>
<td>Very low</td>
</tr>
<tr>
<td>Rogers RO4003</td>
<td>3.38</td>
<td>0.0027</td>
<td>high</td>
</tr>
<tr>
<td><strong>Rogers RO3010</strong></td>
<td><strong>10.2</strong></td>
<td><strong>0.0035</strong></td>
<td><strong>Very high</strong></td>
</tr>
<tr>
<td>Rogers RT/Duroid 6002</td>
<td>2.94</td>
<td>0.0012</td>
<td>high</td>
</tr>
<tr>
<td>Arlon DiClad 880</td>
<td>2.2</td>
<td>0.0009</td>
<td>high</td>
</tr>
<tr>
<td>Rogers RT/Duroid 6006</td>
<td>6.15</td>
<td>0.0019</td>
<td>high</td>
</tr>
<tr>
<td><strong>Rogers RT/Duroid 6010</strong></td>
<td><strong>10.2</strong></td>
<td><strong>0.0023</strong></td>
<td><strong>Very high</strong></td>
</tr>
<tr>
<td>Rogers RO3203</td>
<td>3.02</td>
<td>0.0016</td>
<td>high</td>
</tr>
<tr>
<td>Rogers RT/Duroid 5870</td>
<td>2.33</td>
<td>0.0012</td>
<td>high</td>
</tr>
<tr>
<td>Rogers RT/Duroid 5880</td>
<td>2.2</td>
<td>0.0009</td>
<td>high</td>
</tr>
<tr>
<td><strong>Microwave Dielectric Ceramics</strong></td>
<td><strong>7~300</strong></td>
<td><strong>&lt;&lt;0.001</strong></td>
<td>low</td>
</tr>
</tbody>
</table>

- Almost all the microwave devices were fabricated on the FR4, RO, and Duroid substrates.
Introduction -- Background

The tendencies of microwave dielectric materials for high frequency applications

Because $Q \times f = \text{constant}$ for $f < 20 \ \text{GHz}$,

$Q \uparrow \quad f \quad Q \downarrow \quad \text{loss tangent} (= 1/Q) \uparrow$

high $Q \times f$ materials are needed for high frequency applications.

i.e. Microwave dielectric materials, Superconductors.

All the $Q \times f$ value of modern substrates (FR4 and RO) are only 100-5,000 GHz, but the $Q \times f$ value of the microwave dielectric materials are about 10,000-300,000 GHz.

Velocity $v = f \times \lambda = c / \varepsilon_r^{1/2}$, the size of resonators are $\lambda/2$, $\lambda/4$, $\lambda/8$ etc., usually.

For the purpose of miniaturization, high $\varepsilon_r$ materials are needed in the future.
# Introduction -- Background

## General Microwave Dielectric Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dielectric Constant $\varepsilon_r$</th>
<th>$Q\times f$ (GHz)</th>
<th>$\tau_f$ (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaTiO$_3$</td>
<td>37.96</td>
<td>10,000</td>
<td>+15</td>
</tr>
<tr>
<td>Ba$_2$Ti$<em>3$O$</em>{20}$</td>
<td>30.4</td>
<td>46,000</td>
<td>+5</td>
</tr>
<tr>
<td>(ZrSn)TiO$_4$</td>
<td>38</td>
<td>49,000</td>
<td>≈0</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>9.8</td>
<td>300,000</td>
<td>−55</td>
</tr>
<tr>
<td>Nd$_2$O$_3$-BaO-TiO$_2$-PbO</td>
<td>88</td>
<td>10,000</td>
<td>≈0</td>
</tr>
<tr>
<td>MgTiO$_3$-CaTiO$_3$</td>
<td>221</td>
<td>56,000</td>
<td>+2</td>
</tr>
<tr>
<td>Ba(ZnTa)O$_3$</td>
<td>30</td>
<td>168,000</td>
<td>≈0</td>
</tr>
<tr>
<td>(1-x)Al$_2$O$_3$-xTiO$_2$</td>
<td>7~9.5</td>
<td>5,500~11,000</td>
<td>−60~ +40</td>
</tr>
<tr>
<td>(ZrSn)TiO$_4$</td>
<td>38</td>
<td>49,000</td>
<td>≈0</td>
</tr>
<tr>
<td>Ba(Mg$<em>{1/3}$Ta$</em>{2/3}$)O$_3$</td>
<td>23~25</td>
<td>200,000</td>
<td>−5</td>
</tr>
<tr>
<td>BiNbO$_4$</td>
<td>48</td>
<td>10,000</td>
<td>0~5</td>
</tr>
<tr>
<td>BaO-Sm$_2$O$_3$-TiO$_2$</td>
<td>75</td>
<td>10,000</td>
<td>≈0</td>
</tr>
<tr>
<td>(PbCa)(ZrTi)O$_3$</td>
<td>120</td>
<td>4,500</td>
<td>+5</td>
</tr>
<tr>
<td>MgNb$_2$O$_6$</td>
<td>21</td>
<td>93,800</td>
<td>−70</td>
</tr>
<tr>
<td>MgTa$_2$O$_6$</td>
<td>30.3</td>
<td>59,600</td>
<td>+30</td>
</tr>
<tr>
<td>ZnNb$_2$O$_6$</td>
<td>23.9</td>
<td>77,270</td>
<td>−58</td>
</tr>
<tr>
<td>ZnTa$_2$O$_6$</td>
<td>36.1</td>
<td>60,180</td>
<td>+9.3</td>
</tr>
<tr>
<td>AB$_2$O$_6$ (A=Mg,Zn;B=Nb,Ta)</td>
<td>20~37</td>
<td>30,000~70,000</td>
<td>≈0</td>
</tr>
</tbody>
</table>
Introduction -- Background

The tendencies of Microwave Devices

- **Miniaturization.**
  - High $\varepsilon_r$ Substrates.
  - Structure Modification.

- **Higher Frequency Applications.**
  - High $\varepsilon_r$ and High $Q \times f$ materials.

- **Multi-Band** Applications. (number of band $\geq 2$)
  - Structure Modification.

- **Wide-Band and Ultra-Wide-Band** Applications.
  - Structure Modification.
  - Increasing of Orders.
  - Tunable Transmission Zeros.

- **Bio-devices and its Applications.**
  - Implantable Devices.

High $\varepsilon_r$ and High $Q \times f$ microwave dielectric materials are the most important materials in the future.
**AB$_2$O$_6$ Microwave Dielectric Ceramics**

- Combine ZnNb$_2$O$_6$ (negative $\tau_f$) and ZnTa$_2$O$_6$ (positive $\tau_f$) to form Zn(TaNb)$_2$O$_6$ ($\tau_f \approx 0$ ppm/°C).

  \[ \text{ZnO} + 2x\text{Nb}_2\text{O}_6 + 2(1-x)\text{Ta}_2\text{O}_6 = \text{Zn(Ta}_{1-x}\text{Nb}_x)\text{O}_6 \]

- Combine MgNb$_2$O$_6$ (negative $\tau_f$) and MgTa$_2$O$_6$ (positive $\tau_f$) to form Mg(TaNb)$_2$O$_6$ ($\tau_f \approx 0$ ppm/°C).

  \[ \text{MgO} + 2x\text{Nb}_2\text{O}_6 + 2(1-x)\text{Ta}_2\text{O}_6 = \text{Mg(Ta}_{1-x}\text{Nb}_x)\text{O}_6 \]

**Planar Filters Fabricated on the AB$_2$O$_6$ Ceramics**

- Wide-Band/Dual-Band Bandpass Filters
- Tri-Band/Tetra-Band Bandpass Filters
# Introduction -- Motivation

Microwave dielectric properties of ZnTa$_2$O$_6$ and ZnNb$_2$O$_6$ ceramics

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sintering Temperature ($°$C)</th>
<th>$Q \times f$ (GHz)</th>
<th>$\varepsilon_r$</th>
<th>$\tau_f$ (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnTa$_2$O$_6$</td>
<td>1250</td>
<td>40,500</td>
<td>32.4</td>
<td>8.24</td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>60,180</td>
<td>36.1</td>
<td>9.31</td>
</tr>
<tr>
<td></td>
<td>1350</td>
<td>58,300</td>
<td>36.7</td>
<td>9.24</td>
</tr>
<tr>
<td>ZnNb$_2$O$_6$</td>
<td>1150</td>
<td>47,500</td>
<td>19.5</td>
<td>-63.2</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>77,270</td>
<td>23.9</td>
<td>-58.2</td>
</tr>
<tr>
<td></td>
<td>1250</td>
<td>78,030</td>
<td>24.2</td>
<td>-57.4</td>
</tr>
</tbody>
</table>

Microwave dielectric properties of MgTa$_2$O$_6$ and MgNb$_2$O$_6$ ceramics

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sintering Temperature ($°$C)</th>
<th>$Q \times f$ (GHz)</th>
<th>$\varepsilon_r$</th>
<th>$\tau_f$ (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgTa$_2$O$_6$</td>
<td>1,400</td>
<td>28,500</td>
<td>25.2</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>1,450</td>
<td>44,300</td>
<td>28.9</td>
<td>27.1</td>
</tr>
<tr>
<td></td>
<td>1,500</td>
<td>56,900</td>
<td>30.5</td>
<td>28.3</td>
</tr>
<tr>
<td></td>
<td>1,550</td>
<td>58,200</td>
<td>30.6</td>
<td>28.5</td>
</tr>
<tr>
<td>MgNb$_2$O$_6$</td>
<td>1,300</td>
<td>34,100</td>
<td>15.7</td>
<td>-78.0</td>
</tr>
<tr>
<td></td>
<td>1,350</td>
<td>66,500</td>
<td>20.5</td>
<td>-69.1</td>
</tr>
<tr>
<td></td>
<td>1,400</td>
<td>89,900</td>
<td>21.7</td>
<td>-68.5</td>
</tr>
<tr>
<td></td>
<td>1,450</td>
<td>91,500</td>
<td>21.8</td>
<td>-68.3</td>
</tr>
</tbody>
</table>
TOPICS

Introduction
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\(AB_2O_6\) Microwave Dielectric Ceramics
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Planar Filters
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• Discussion

Conclusions and Future Works
Theory -- Planar Filters

- Metal microstrip line
- Dielectric substrate $\varepsilon_r$
- Metal ground plane

- E line
- H line

- E line
- Substrate $\varepsilon_r$
- h
Theory -- Planar Filters

(a) Electric coupling

(b) Magnetic coupling

(c) Mixed coupling

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Theory -- Planar Filters

End-Coupling

Bend

SIR

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TOPICS

Introduction
  • Background
  • Motivation

Theory and Experimental
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  • Planar Filters

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Planar Filters
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Conclusions and Future Works
**AB_2O_6 Microwave Dielectric Ceramics**

**ZnTa_{2-x}Nb_xO_6 Ceramics**

![X-ray diffraction patterns of ZnTa_2O_6 and ZnNb_2O_6](image)

<table>
<thead>
<tr>
<th>x value</th>
<th>S_T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 0</td>
<td>1300</td>
</tr>
<tr>
<td>(b) 0.3</td>
<td>1250</td>
</tr>
<tr>
<td>(c) 0.6</td>
<td>1250</td>
</tr>
<tr>
<td>(d) 1.0</td>
<td>1250</td>
</tr>
<tr>
<td>(e) 1.4</td>
<td>1250</td>
</tr>
<tr>
<td>(f) 1.7</td>
<td>1200</td>
</tr>
<tr>
<td>(g) 2.0</td>
<td>1200</td>
</tr>
</tbody>
</table>

o: ZnTa_2O_6 orthorhombic structure
x: ZnNb_2O_6 orthorhombic structure
**AB₂O₆ Microwave Dielectric Ceramics**

**ZnTa₂₋ₓNbₓO₆ Ceramics**

- ZnTa₂O₆ (x=0) ceramics sintered at 1300°C reveal a single phase which belongs to orthorhombic structure with space group Pnab(60) and a=5.065 Å, b=17.078 Å, and c=4.694 Å.

- ZnNb₂O₆ (x=2) ceramics sintered at 1200°C reveal a single phase which belongs to orthorhombic structure with space group Pnab(60) and a=5.720 Å, b=14.178 Å, and c=5.306 Å.

- The 2θ shifts to higher values as the Nb₂O₅ content increases, which cause the variations of lattice constants and unit volume.

- The ZnTa₂O₆ and ZnNb₂O₆ ceramics exactly form a solid solution.
AB$_2$O$_6$ Microwave Dielectric Ceramics

ZnTa$_{2-x}$Nb$_x$O$_6$ Ceramics

\[ V \times \ln(\varepsilon_r) = \sum V_i \times \ln(\varepsilon_{ri}) \quad (3-2) \]
\[ \alpha(\text{AB}_2\text{O}_6) = \alpha(\text{A}^{2+}) + 2\alpha(\text{B}^{5+}) + 6\alpha(\text{O}^{2-}) \quad (3-5) \]

<table>
<thead>
<tr>
<th>Ion polarizability</th>
<th>( (\text{Å}^3) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta$^{5+}$</td>
<td>4.73</td>
</tr>
<tr>
<td>Nb$^{5+}$</td>
<td>3.97</td>
</tr>
<tr>
<td>Zn$^{2+}$</td>
<td>2.04</td>
</tr>
<tr>
<td>O$^{2-}$</td>
<td>2.01</td>
</tr>
</tbody>
</table>


- As Nb$_2$O$_5$ (X value) increase, the density decrease. The reasons are:
  1. Unit volume
  2. Total mass (Ta>Nb)
AB$_2$O$_6$ Microwave Dielectric Ceramics

ZnTa$_{2-x}$Nb$_x$O$_6$ Ceramics

- 1300°C-sintered ZnTa$_2$O$_6$
- 1250°C-sintered ZnTa$_{1.4}$Nb$_{0.6}$O$_6$
- 1250°C-sintered ZnTa$_{1.0}$Nb$_{1.0}$O$_6$
- 1250°C-sintered ZnTa$_{0.6}$Nb$_{1.4}$O$_6$
- 1200°C-sintered ZnNb$_2$O$_6$
**AB$_2$O$_6$ Microwave Dielectric Ceramics**

**ZnTa$_{2-x}$Nb$_x$O$_6$ Ceramics**

<table>
<thead>
<tr>
<th>x</th>
<th>0.0</th>
<th>0.3</th>
<th>0.6</th>
<th>1.0</th>
<th>1.4</th>
<th>1.7</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_T$ ($^\circ$C)</td>
<td>1300</td>
<td>1250</td>
<td>1250</td>
<td>1250</td>
<td>1250</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Morphology</td>
<td>D</td>
<td>D</td>
<td>D-B</td>
<td>D-B</td>
<td>D-B</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

(D: disk-typed grain, B: bar-typed grain)

The appropriate sintering temperature is lowered down as the Nb$_2$O$_5$ content increases, and the grains change gradually from disk-typed to bar-typed.
AB$_2$O$_6$ Microwave Dielectric Ceramics

ZnTa$_{2-x}$Nb$_x$O$_6$ Ceramics

1/Q = $\sum V_i / Q_i$  \hspace{1cm} (3-3)

$\tau_f = \sum V_i \times \tau_{fi}$  \hspace{1cm} (3-4)

- Both bar-typed and disk-typed grains co-exist as $0.6 \leq x \leq 1.4$.

- As the Nb$_2$O$_5$ content increases, both of the estimated and measured $\tau_f$ values vary from positive values ($x \leq 0.3$) to negative ones ($x \geq 0.7$).

- This means that a near zero $\tau_f$ could be obtained at about $X = 0.3$. 
AB$_2$O$_6$ Microwave Dielectric Ceramics

ZnTa$_{1.7}$Nb$_{0.3}$O$_6$ Ceramics

The microwave dielectric properties of ZnTa$_2$O$_6$ ceramics (sintered at 1300°C, $\tau_f=+9.31$ ppm/°C, $\varepsilon_r=36.1$, and $Q\times f=60,180$ GHz) and ZnNb$_2$O$_6$ ceramics (sintered at 1200°C, $\tau_f=-58.2$ ppm/°C, $\varepsilon_r=23.9$, and $Q\times f=77,270$ GHz) are used as the reference data.

$\tau_f$ value close to 0 ppm/°C are predicted to be:

$0$ ppm/°C = $\sum V_i \tau_i = V_1 \tau_1 + V_2 \tau_2 = V_1 \times 9.31 + V_2 \times (-58.2)$

$V_1 / V_2 = -\tau_2 / \tau_1 = 58.2 / 9.31 = 6.25 = (M_1 \times P_1 / d_1) / (M_2 \times P_2 / d_2)$,

where subscripts 1 and 2 denote ZnTa$_2$O$_6$ and ZnNb$_2$O$_6$, respectively, and d, M, and P denote density, molecular weight, and mole ratio, respectively, and $d_1=8.184$ g/cm$^3$, $d_2=5.436$ g/cm$^3$, $M_1=523.276$ g/mole, and $M_2=347.193$ g/mole.

$$\begin{cases} 6.251 = \frac{P_1}{P_2} \\ P_1 + P_2 = 2 \end{cases}$$

$P_1=1.72$  
$P_2=0.28$

ZnTa$_{1.72}$Nb$_{0.28}$O$_6$
• Higher sintering temperatures will cause grain growth and fewer pores, which result in higher $\varepsilon_r$ and density.
AB₂O₆ Microwave Dielectric Ceramics
Mg(Ta₁₋ₓNbₓ)₂O₆ Ceramics

- For \( x = 0 \) (MgTa₂O₆), the solid solution show tetragonal structure.
- For \( x = 0.15 \), the solid solution has the coexistence of tetragonal and orthorhombic structure.
- For \( 0.25 \leq x \leq 1 \), the solid solution exhibits orthorhombic structure.
- The crystalline phase transition (changes from tetragonal to orthorhombic) occurs at a particular composition between \( X=0.1\sim0.2 \).

[+: tetragonal, ×: orthorhombic]
**AB$_2$O$_6$ Microwave Dielectric Ceramics**

Mg(Ta$_{1-x}$Nb$_x$)$_2$O$_6$ Ceramics

- $X=0$, $S_T=1500^\circ C$
- $X=0.15$, $S_T=1500^\circ C$
- $X=0.35$, $S_T=1450^\circ C$
- $X=0.5$, $S_T=1400^\circ C$
- $X=0.7$, $S_T=1400^\circ C$
- $X=0.85$, $S_T=1350^\circ C$
- $X=1$, $S_T=1300^\circ C$

Bar=5  m
AB$_2$O$_6$ Microwave Dielectric Ceramics

Mg(Ta$_{1-x}$Nb$_x$)$_2$O$_6$ Ceramics

- As $S_T$ increased, the M.D. first increase, and then saturate at a certain temperature.
- The temperatures to reach the saturated density values decrease with the increase of MgNb$_2$O$_6$ content.
- Both of the M.D. and T.D. decrease with the increase of MgNb$_2$O$_6$ content, the lower density values of MgNb$_2$O$_6$ ceramics and the substitution of heavier Ta atoms by lighter Nb atoms are the reason.
- The M.D. can be up to 98.8% at $x = 0.15$, and then critically decreased below 95% at $0.25 \leq x \leq 0.7$. The coexistence of dual-typed grains would be the reason.
- At $0.85 \leq x \leq 1$, because only bar-typed grains existed, the densities are higher than 95.8%.

[+:measured density, ●: theoretical density]
AB$_2$O$_6$ Microwave Dielectric Ceramics

Discussion

The sintering behaviors and microwave dielectric characteristics of AB$_2$O$_6$ ceramics are influenced by the sintering temperature and Nb$_2$O$_5$ content, including grain growth, dielectric constant, quality factor, and $\tau_f$ value.

For Zn(Ta$_{1-x}$Nb$_x$)$_2$O$_6$ microwave dielectric ceramics, when the Nb$_2$O$_5$ content increases, the dielectric constant and density decrease, and the $\tau_f$ value changes from +9.24 ppm/°C (x=0) to −58.2 ppm/°C (x=1).

The 1300°C-sintered ZnTa$_{1.7}$Nb$_{0.3}$O$_6$ ceramics reveal the optimum microwave dielectric characteristics of $\varepsilon_r = 35.2$, $Q\times f = 53,100$ GHz, and $\tau_f = 3.0$ ppm/°C.
AB$_2$O$_6$ Microwave Dielectric Ceramics

Discussion

For Mg(Ta$_{1-x}$Nb$_x$)$_2$O$_6$ microwave dielectric ceramics, the optimum sintering temperature decreased with the increase of Nb content, and ranged from 1500 to 1300°C as x increased from 0 to 1.

The phases transit from tetragonal (MgTa$_2$O$_6$) to orthorhombic (MgNb$_2$O$_6$) as the Nb content increase, and both structures coexist at 0.1 ≤ x ≤ 0.2.

The saturated $\tau_f$ values of Mg(Ta$_{1-x}$Nb$_x$)$_2$O$_6$ ceramics (0.25≤x≤0.35) are all within the range of $-4.1$~$-0.7$ ppm/°C.

The 1450°C-sintered MgTa$_{1.5}$Nb$_{0.5}$O$_6$ ceramics reveal the optimum microwave dielectric characteristics of of $\varepsilon_r = 27.9$, $Q\times f = 33,100$ GHz, and $\tau_f = -0.7$ ppm/°C.
TOPICS

Introduction
- Background
- Motivation

Theory and Experimental
- $\text{AB}_2\text{O}_6$ Microwave Dielectric Ceramics
- Planar Filters

$\text{AB}_2\text{O}_6$ Microwave Dielectric Ceramics
- $\text{Zn(TaNb)}_2\text{O}_6$ Ceramics
- $\text{Mg(TaNb)}_2\text{O}_6$ Ceramics
- Discussion

Planar Filters
- Wide-Band/Dual-Band Filters
- Tri-band/Tetra-Band Filters
- Discussion

Conclusions and Future Works

National University of Kaohsiung
Planar Filters

**Motivation 1**: Up to now, only few researchers fabricated microwave devices on the Al₂O₃ substrates (εᵣ=9.8, Q×f=300,000 GHz, and τᵣ=-55 ppm/°C). But the τᵣ and εᵣ values of Al₂O₃ still not good enough for the applications in the microwave communication systems.

**Motivation 2**: The dielectric constant (εᵣ=27.9) of MgTa₁₋₀.₅Nb₀.₅O₆ is greater than Al₂O₃ or any other modern used substrates (FR4 and RO), and this substrates would reduce the size of the devices effectively.

**Motivation 3**: Even the quality factor of MgTa₁₋₀.₅Nb₀.₅O₆ (Q×f=33,100 GHz) is smaller than Al₂O₃, but comparing to FR4 and RO, this quality is good enough.

**Motivation 4**: The **combination technique** is adopted to design the wide-band/dual-band/tri-band/tetra-band bandpass filters.
Planar Filters

MgTa\textsubscript{1.5}Nb\textsubscript{0.5}O\textsubscript{6} substrate

Simulated by HFSS

Mask Fabrication

Pattern Screen-printing

Firing (800°C/30min)

Soldering SMA Connectors

Characteristics Measuring (HP8720)

\begin{align*}
\varepsilon_r &= 27.9 \\
Q \times f &= 33,100 \\
\tau_f &= -0.7 \text{ ppm/°C}
\end{align*}
Planar Filters

Wide-Band/Dual-Band Filters

Parallel-coupled Lines

MgTa_{1.5}Nb_{0.5}O_6 substrate \( \varepsilon_t = 27.9 \)
Planar Filters

Wide-Band/Dual-Band Filters

Frequency (GHz)

Magnitude (dB)

Unit:mm

S11

S21

Port 1

Port 2

0.6

0.4

2.4

4

3.2

0.3

13

0.3
Planar Filters

Wide-Band/Dual-Band Filters

Using modified end-coupled structure to generate a dual-band (2.45 / 5.2 GHz) bandpass filter with two transmission zeros

Using a $\lambda/2$ hairpin resonator to generate a zero at the upper skirt of 5.2 GHz

Combining above two structures
Planar Filters

Wide-Band/Dual-Band Filters

Frequency (GHz)

Unit:mm

$S_{21} (\text{dB})$

Frequency (GHz)

Unit:mm

$S_{21} (\text{dB})$

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Planar Filters

Wide-Band/Dual-Band Filters

Using modified end-coupled structure to generate a dual-band (2.45 / 5.2 GHz) bandpass filter with two transmission zeros

Using a $\lambda/2$ hairpin resonator to generate a zero at the upper skirt of 5.2 GHz

Combining above two structures

Type A

Type B

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Planar Filters

Discussion—Wide-Band/Dual-Band Filters

![Diagram of Planar Filters]

- Type A

**Diagram Description:**
- MgTa$_{1.9}$Nb$_{0.5}$O$_5$ substrate
- \( \varepsilon_r = 27.9 \), thickness = 1 mm
- Microstrip line
- Ground plane

**Graph:**
- Magnitude (dB) vs. Frequency (GHz)
- \(--\) Simulated \( S_{11} \)
- \(---\) Simulated \( S_{21} \)
- \(----\) Measured \( S_{21} \)

**Graph Details:**
- Frequency range: 1 to 8 GHz
- Magnitude range: -80 dB to 0 dB

---

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---
Planar Filters

Discussion—Wide-Band/Dual-Band Filters

MgTa$_{1.9}$Nb$_{3.3}$O$_6$ substrate
($\varepsilon=27.9$, thickness=1 mm)

Microstrip line

MgTa$_{1.9}$Nb$_{3.3}$O$_6$ substrate, $\varepsilon=27.9$, thickness=1 mm

Ground plane

Type B

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## Planar Filters

### Discussion—Wide-Band/Dual-Band Filters

<table>
<thead>
<tr>
<th>Type</th>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz / %)</th>
<th>Insertion Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.45</td>
<td>310 / 12.6 (340 / 13.8)</td>
<td>0.16 (0.18)</td>
</tr>
<tr>
<td>B</td>
<td>2.45</td>
<td>370 / 15.1 (375 / 15.3)</td>
<td>0.14 (0.16)</td>
</tr>
<tr>
<td>A</td>
<td>5.2</td>
<td>1200 / 23 (1210 / 23.2)</td>
<td>0.38 (0.64)</td>
</tr>
<tr>
<td>B</td>
<td>5.2</td>
<td>970 / 18.6 (955 / 18.3)</td>
<td>0.38 (0.72)</td>
</tr>
</tbody>
</table>

**Simulated (Measured)**

<table>
<thead>
<tr>
<th>Type</th>
<th>Band (GHz)</th>
<th>Bandwidth (MHz)[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>5.15<del>5.35/5.725</del>5.825</td>
<td>200/100[3.85/1.73]</td>
</tr>
<tr>
<td>802.11b</td>
<td>2.4~2.4835</td>
<td>83.5[3.42]</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4~2.4835</td>
<td>83.5[3.42]</td>
</tr>
<tr>
<td>GPS</td>
<td>1.57542</td>
<td>20[1.27]</td>
</tr>
<tr>
<td>WiMAX</td>
<td>2.56<del>2.69/3.4</del>3.69/5.25~5.85</td>
<td>130/290/600[5/8.2/10.8]</td>
</tr>
</tbody>
</table>
Planar Filters

Tri-band/Tetra-Band Filters

- Use an outer-frame structure to generate 1.57 GHz
- Use a $\lambda/2$ U-shaped resonator to generate 2.45 GHz
- Use a modified $\lambda/2$ end-coupled structure to generate 2.45 and 5.2 GHz
- Use Defected Ground Structure (DGS) to modify 3.5 GHz.

- Tri-band Bandpass Filters (1.57/2.45/5.2 GHz)
- Tetra-band Bandpass Filters (1.57/2.45/3.5/5.2 GHz)

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Planar Filters

Tri-band/Tetra-Band Filters

Magnitude (dB)

Port 1

Port 2

Frequency (GHz)

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Planar Filters

Tri-band/Tetra-Band Filters

Use an outer-frame structure to generate 1.57 GHz

Use a $\lambda/2$ U-shaped resonator to generate 2.45 GHz

Combined

Use a modified $\lambda/2$ end-coupled structure to generate 2.45 and 5.2 GHz

Tri-band Bandpass Filters (1.57/2.45/5.2 GHz)

Use Defected Ground Structure (DGS) to modify 3.5 GHz.

Tetra-band Bandpass Filters (1.57/2.45/3.5/5.2 GHz)

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Planar Filters

Tri-band/Tetra-Band Filters

Magnitude (dB)

Frequency (GHz)

Port 1

Port 2

S11

S21

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Planar Filters

Tri-band/Tetra-Band Filters

Use an outer-frame structure to generate 1.57 GHz

Use a $\lambda/2$ U-shaped resonator to generate 2.45 GHz

Combined

Tri-band Bandpass Filters
(1.57/2.45/5.2 GHz)

Use Defected Ground Structure (DGS) to modify 3.5 GHz.

Tetra-band Bandpass Filters
(1.57/2.45/3.5/5.2 GHz)

Use a modified $\lambda/2$ end-coupled structure to generate 2.45 and 5.2 GHz

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Planar Filters

Tri-band/Tetra-Band Filters

Magnitude (dB)

Frequency (GHz)

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Planar Filters

Tri-band/Tetra-Band Filters

- Use an outer-frame structure to generate 1.57 GHz
- Use a $\lambda/2$ U-shaped resonator to generate 2.45 GHz
- Use a modified $\lambda/2$ end-coupled structure to generate 2.45 and 5.2 GHz

Combined

- Tri-band Bandpass Filters (1.57/2.45/5.2 GHz)
- Use Defected Ground Structure (DGS) to modify 3.5 GHz

- Tetra-band Bandpass Filters (1.57/2.45/3.5/5.2 GHz)

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Planar Filters

Tri-band/Tetra-Band Filters

Frequency (GHz)

Magnitude (dB)

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Planar Filters

Tri-band/Tetra-Band Filters

Magnitude (dB)

Frequency (GHz)

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Planar Filters

Tri-band/Tetra-Band Filters

- Use an outer-frame structure to generate 1.57 GHz
- Use a λ/2 U-shaped resonator to generate 2.45 GHz
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- Use a modified λ/2 end-coupled structure to generate 2.45 and 5.2 GHz

Combined

Tri-band Bandpass Filters (1.57/2.45/5.2 GHz)

Tetra-band Bandpass Filters (1.57/2.45/3.5/5.2 GHz)

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Planar Filters

Tri-band/Tetra-Band Filters

\[ S_{21} \text{ (dB)} \]

Frequency (GHz)

3 3.5 4 4.5

-50 -40 -30 -20 -10 0

W = 0.3 mm
W = 0.5 mm
W = 0.7 mm

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Planar Filters

Tri-band/Tetra-Band Filters

- DGS (ground plane)
- \( \lambda/2 \) resonator
- End-coupled
- Microstrip line
- SIR
- Outer-frame
- High impedance resonator
- U-shaped resonator

Size: 26.3mm \( \times \) 9.9mm
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Planar Filters

Tri-band/Tetra-Band Filters

Magnitude (dB)

-60 -50 -40 -30 -20 -10 0

Frequency (GHz)

1 2 3 4 5 6 7

S_{11}  S_{21}

Port 1  Port 2

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Conclusions and Future Works

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Planar Filters

Top-view

Ground Plane

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Planar Filters

Discussion—Tri-band/Tetra-Band Filters

The diagram shows the frequency response of Planar Filters with the following key points:

- **S21 (dB)**: The vertical axis represents the signal-to-noise ratio in decibels.
- **Frequency (GHz)**: The horizontal axis represents the frequency in gigahertz.
- **Key Frequencies**:
  - 1.57 GHz
  - 2.45 GHz
  - 3.5 GHz
  - 5.2 GHz

The plot compares the simulated and measured data, with the simulated data shown as dashed lines and the measured data as solid lines. The graph indicates a good match between simulation and measurement across the specified frequency bands.
Conclusions-- Paper Review---- Tri-band filter

(Pattern I)

(Pattern II)

Paper 1


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Conclusions

Paper 2


*IEEE Microwave and Wireless Components Letters, 16 (2006) 594*

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### Comparing with the Lectures

<table>
<thead>
<tr>
<th></th>
<th>Frequency (GHz)</th>
<th>Bandwidth (%)</th>
<th>Loss (dB)</th>
<th>Size (mm×mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper 1 (Pattern I)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>4</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.6</td>
<td>4</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.1</td>
<td>6</td>
<td>2.3</td>
<td>≈50×35</td>
</tr>
<tr>
<td>Paper 1 (Pattern II)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>3.8</td>
<td>2.5</td>
<td>≈60×40</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>6.8</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>5</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Paper 2</td>
<td>1.57</td>
<td>8.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.45</td>
<td>7.3</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>9.9</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>My Tetra-Band Filter</td>
<td>1.57</td>
<td>9.55</td>
<td>0.31</td>
<td>26.3×9.9</td>
</tr>
<tr>
<td></td>
<td>2.45</td>
<td>31.84</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>11.1</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>15.96</td>
<td>0.78</td>
<td></td>
</tr>
</tbody>
</table>

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### Planar Filters

#### Discussion—Tri-band/Tetra-Band Filters

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz / %)</th>
<th>Insertion Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.57</td>
<td>130 / 8.3 (150 / 9.55 )</td>
<td>0.19 (0.31)</td>
</tr>
<tr>
<td>2.45</td>
<td>760 / 31 (780 / 31.84 )</td>
<td>0.18 (0.32)</td>
</tr>
<tr>
<td>3.5</td>
<td>380 / 10.8 (390 / 11.1 )</td>
<td>0.24 (0.31)</td>
</tr>
<tr>
<td>5.2</td>
<td>750 / 14.1 (830 / 15.96 )</td>
<td>0.59 (0.78)</td>
</tr>
</tbody>
</table>

Simulated (Measured)

<table>
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• $\text{Mg(TaNb)}_2\text{O}_6$ Ceramics
• Discussion

Planar Filters
• Wide-Band/Dual-Band Filters
• Tri-band/Tetra-Band Filters
• Discussion

Conclusions and Future Works
Conclusions—Wide-Band/Dual-Band Filters

The optimum measured characteristics of the dual-band filters are:

Type A:
- 2.45 GHz: Bandwidth **340 MHz (13.8%)**; Insertion loss **0.18 dB**.
- 5.2 GHz: Bandwidth **1210 MHz (23.2%)**; Insertion loss **0.64 dB**.

Type B:
- 2.45 GHz: Bandwidth **375 MHz (15.3%)**; Insertion loss **0.16 dB**.
- 5.2 GHz: Bandwidth **955 MHz (18.3%)**; Insertion loss **0.72 dB**.

Using the combination technique and high dielectric constant substrates, the filters are designed easily and the size could be miniaturized to **26.3 mm × 3.7 mm** for Type A and **26.3 mm × 5.5 mm** for Type B.
Conclusions—Tri-Band/Tetra-Band Filters

Up to **six** deeply transmission zeros were generated between the pass bands to improve the performance of the filters (1~7 GHz).

The optimum measured characteristics of these four pass bands are:

- 1.57 GHz: Bandwidth **150 MHz** (9.55%); Insertion loss **0.31 dB**.
- 2.45 GHz: Bandwidth **780 MHz** (31.84%); Insertion loss **0.32 dB**.
- 3.5 GHz: Bandwidth **390 MHz** (11.1%); Insertion loss **0.31 dB**.
- 5.2 GHz: Bandwidth **830 MHz** (15.96%); Insertion loss **0.78 dB**.

Using the combination technique and high dielectric constant substrates, the filters are designed easily and the size could be miniaturized to only **26.3 mm × 9.9 mm**.

The microwave dielectric ceramic substrate would be an important microwave substrate for the development of higher frequency microwave devices in the future.
Q & A

Thanks for Your Attentions