MM-WAVE CHARACTERISTICS AND APPLICATIONS OF HEXAFERRITE CERAMICS AND NON-COLLINEAR ANTIFERROMAGNETS

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OVERVIEW

- MM-Wave Instrumentation and Measurement Method
- Microwave Characteristics of Hexaferrite Ceramics
- Confined-Field Circulator: Concept and Implementation
- Non-Collinear Antiferromagnets for MM-Wave Applications
- Summary
BEAM FORMING ARRANGEMENT OF THE QUASI-OPTICAL BWO SPECTROMETER

TECHNICAL CHARACTERISTICS

- TUNING RANGE: 35 – 600 GHz
- MM-WAVE SOURCE: Backward Wave Oscillators (BWO-s)
- DETECTOR: Diodes/Bolometers
- RESOLUTION: < 3 MHz
- DYNAMIC RANGE: > 40 dB
- MAGNETIC FIELD: 15 kOe
- SCAN TIME (1000 point): 1 min.
**OPTICS OF LAYERED MEDIA**

\[
T = \frac{I_T}{I_0} = E \frac{(1 - R_0)^2}{(1 - R_0 E)^2 + 4 R_0 E \sin^2 \alpha}
\]

\[
R = \frac{I_R}{I_0} = \frac{R_0 (1 - E^2)}{(1 - R_0 E)^2 + 4 R_0 E \sin^2 \alpha}
\]

\[
R_0 = \left[\frac{\sqrt{\varepsilon} - \sqrt{\mu}}{\sqrt{\varepsilon} + \sqrt{\mu}}\right]^2
\]

\[
E = \exp(-2 \beta) = \exp\left(-\frac{4 \pi k d \nu}{c}\right)
\]

\[
\alpha = \frac{2 \pi n d \nu}{c}
\]

\[
n + ik = \sqrt{\mu^* \varepsilon^*}
\]

\[
n^2 - k^2 = (\varepsilon' \mu' - \varepsilon'' \mu'')
\]

\[
k = (\varepsilon'' \mu' + \varepsilon' \mu'')/2n \equiv k_e + k_m
\]
SIMULATION MODEL

1. Dielectric Permittivity:  \( \varepsilon^*/\varepsilon_0 = \varepsilon' - j\varepsilon'' \)

\[
\varepsilon'(f) = \varepsilon_0' + d\varepsilon'/df \times f;
\]

\[
\varepsilon''(f) = \varepsilon_0'' + d\varepsilon''/df \times f + 18\times\sigma\text{(Ohm m)}^{-1}/f\text{(GHz)};
\]

2. Magnetic Permeability:  \( \mu^*/\mu_0 = \mu' - j\mu'' \)

Isotropic magnetized ferrites (configuration \( \mathbf{M} \perp \mathbf{h}, \mathbf{k} \)):

\[
\frac{\mu^*}{\mu_0} = \frac{[(f_0^* + f_M)^2 - f^2]/[f_0^* (f_0^* + f_M) - f^2]}{[f_0^*]^2 - f^2]} \quad \text{(Polder)}
\]

Anisotropic ferrites:

a) Non-oriented demagnetized:

\[
\frac{\mu^*}{\mu_0} = \frac{1/3 + 2/3 \sqrt{\left\{(f_A^* + f_M)^2 - f^2\right\}/[f_A^*]^2 - f^2}}{[f_A^*]^2 - f^2]} \quad \text{(Schloemann)}
\]

b) Oriented demagnetized (\( \mathbf{A} \parallel \mathbf{k} \), where \( \mathbf{A} \) – direction of grain orientation):

\[
\frac{\mu^*}{\mu_0} = \sqrt{\left\{(f_A^* + f_M)^2 - f^2\right\}/[f_A^*]^2 - f^2}} \quad \text{(Schloemann)}
\]

\[
\begin{align*}
f_A^* &= (\gamma 2\pi)H_A + jfG \\
f_0^* &= (\gamma 2\pi)H_0 + jfG \\
f_M &= 2\gamma M
\end{align*}
\]

\( H_A \) – anisotropy field; \( H_0 \) – external field, \( G \) – loss parameter
SIMULATION OF MM-WAVE SPECTRA

Best-Fit Parameters:  \( \varepsilon' = 19.7, \quad \varepsilon'' = 0.09 \) @ 30 GHz and 0.093 @ 120 GHz
\[ f_A = 53.2 \text{ GHz}, \quad \alpha_G = 0.0015, \quad 4\pi M = 3.8 \text{ kG} \]
EFFECT OF CONDUCTIVITY ON MM-WAVE PROPERTIES OF HEXAFERRITE CERAMICS

a) Conducting Ceramics

In conducting ceramics the microwave loss decreases with the decrease of temperature.

b) Low-Loss Microwave Ceramics

Fundamental limit at $k \sim 0.004$
MM-WAVE CHARACTERISTICS OF DEMAGNETIZED HEXAFERRITE CERAMICS

Data presented are for the wave propagating along the direction of orientation.
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Manufacturer/Provider</th>
<th>Class of Materials**)</th>
<th>$\varepsilon'$, $\Delta \varepsilon' / df$</th>
<th>$\varepsilon''$, $\Delta \varepsilon'' / df$</th>
<th>$\sigma$ (Ohm m)$^{-1}$</th>
<th>$\alpha_G$</th>
<th>$f_A$, GHz</th>
<th>$f_M$, GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>“Thomas Keating, Ltd.,” UK, (manuf. in China)</td>
<td>Ba-M/O</td>
<td>18.74  0</td>
<td>0.06  0</td>
<td>&lt; 0.05</td>
<td>0.001</td>
<td>50.12</td>
<td>11.2</td>
</tr>
<tr>
<td>M2</td>
<td>“Manatee Magnetic Corp., FL, USA”</td>
<td>Sr-M/O</td>
<td>19.71  0</td>
<td>0.044 0.0003</td>
<td>&lt; 0.05</td>
<td>0.0015</td>
<td>53.2</td>
<td>12.3</td>
</tr>
<tr>
<td>E1</td>
<td>“EDO Electro-Ceramics” UT, USA</td>
<td>Sr-M/O</td>
<td>19.23  0</td>
<td>0.025 0</td>
<td>0.1</td>
<td>0.0015</td>
<td>46.7</td>
<td>12.3</td>
</tr>
<tr>
<td>E2</td>
<td>“EMS-Technologies”, GA, USA</td>
<td>Ba-M/O</td>
<td>21.4  0.001</td>
<td>0.03  0</td>
<td>0.09</td>
<td>0.0017</td>
<td>51.1</td>
<td>11.7</td>
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<tr>
<td>S1</td>
<td>“Superconductive Comp., Inc”, OH, USA</td>
<td>Ba-M/N</td>
<td>17.22  0</td>
<td>0.105 0.0009</td>
<td>&lt; 0.05</td>
<td>0.0019</td>
<td>46.2</td>
<td>12.04</td>
</tr>
<tr>
<td>N3</td>
<td>“Datoyo Corp.”, Ningbo, China</td>
<td>Ba-M/O</td>
<td>18.8  0</td>
<td>0.07  0.0003</td>
<td>0.05</td>
<td>0.0012</td>
<td>47.6</td>
<td>10.6</td>
</tr>
</tbody>
</table>

*) Data shown for the oriented hexaferrite ceramics are for the wave propagating along the direction of orientation.
**) Composition/Alignment: Ba-M = M-type Ba hexagonal ferrite, Sr-M = M-type Sr hexagonal ferrite; O = oriented ceramic, N = non-oriented ceramic.
ANISOTROPY OF ORIENTED HEXAFERRITE CERAMICS

Millimeter Wave Spectra of 8.77 mm Thick Block of Oriented Sr-Hexaferrite Ceramic for two configurations of incident wave polarization and direction of orientation (A – the axis of orientation).
ANISOTROPY OF HIGH-RESISTIVITY HEXAFERRITE CERAMICS

a) Intersection point above the resonance

b) Higher dielectric loss in $e||A$ polarization

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ANISOTROPY OF CONDUCTING HEXAFERRITE CERAMICS

Higher eddy-current loss in \( e \perp A \) configuration.
Soft and hard ferrites are biased above and below the resonance, respectively. The circulation action is in the same direction since the soft and hard ferrites are magnetized in opposite directions.

*) Patent Pending
STRIP-LINE PROTOTYPE OF CONFINED-FIELD CIRCULATOR

Lower Pole Piece

Lower Ground Plate

Ferrite Puck

Central Junction

Hexaferrite Ring

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WAVEGUIDE AND QUASI-OPTICAL DESIGNS OF
CONFINED-FIELD CIRCULATOR

Steel Wall Waveguide

Soft Ferrite

Hexaferrite

Impedance Matching Layer
NON-COLLINEAR ANTIFERROMAGNETS

a) Regular Antiferromagnets

\[ \Sigma 4\pi M_i = 0 \]

b) Non-Collinear Antiferromagnets

\[ \Sigma 4\pi M_i = 4\pi m \sim 100 \text{ Gauss} \]

Principal Effective Magnetic Fields:

\[ H_{D-M} = 0 \]

\[ |H_E| \sim 10^7 \div 10^8 \text{ Oe} \]

\[ |H_A| \sim 10^2 \div 10^3 \text{ Oe} \]

\[ |H_{D-M}| \sim 10^4 \text{ Oe} \]
### Some Symmetry Classes Allowing Non-Collinear Antiferromagnetism

<table>
<thead>
<tr>
<th>Crystal Class</th>
<th>Group</th>
<th>Material</th>
<th>Type of Alignment</th>
<th>( T_N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigonal (Uniaxial)</td>
<td>( D_{3d}^6 )</td>
<td>( \alpha - \text{Fe}_2\text{O}_3 ) (Hematite) ( T &gt; 150 , \text{K} ) ( \text{FeBO}_3 ) ( \text{MCO}_3 ) (M = Fe, Mn, Ni)</td>
<td>Easy-plane</td>
<td>905 K; 348 K; 16 ÷ 54 K</td>
</tr>
<tr>
<td>Tetragonal (Uniaxial)</td>
<td>( D_{4h}^{14} )</td>
<td>NiF(_2) ( \text{MF}_2 ) (M = Fe, Mn, Co)</td>
<td>Easy-plane</td>
<td>Easy-axis</td>
</tr>
<tr>
<td>Orthorhombic</td>
<td>( D_{2h}^{16} )</td>
<td>( \text{RFeO}_3 ) (R = Y or Re) ( \text{Fe}_3\text{BO}_6 ) ( \text{RMnO}_3 ) (R = Y or Re)</td>
<td>Easy-axis</td>
<td>630 ÷ 645 K; 508 K; 65 – 117 K</td>
</tr>
</tbody>
</table>
MAGNETIC EIGEN-MODES IN NON-COLLINEAR ANTIFERROMAGNETS

The number of magnetic resonance modes is equal to the number of magnetic sub-lattices (usually two in antiferromagnets).

a) Quasi-ferromagnetic mode (QFM) (precession)

\[ |m| \approx \text{const} \]

Activation Frequency: Low/Moderate

Selection Rules: \[ h \perp Oz \]

b) Quasi-antiferromagnetic mode (QAM) (oscillation)

\[ |m| \neq \text{const.} \]

Activation Frequency: High

Selection Rules: \[ h \parallel Oz \]
TEMPERATURE VARIATION OF EIGEN-MODE FREQUENCIES

Trigonal AF

\[ \omega_2 / \gamma = \left( 2H_A H_E - H_D^2 \right)^{1/2} \]

\[ \omega_1 / \gamma = 0 \]

Orthorhombic AF

\[ \omega_2 / \gamma = \left( H_{A_0} H_E - H_{D_1} \right)^{1/2} \]

\[ \omega_1 / \gamma = \left[ H_{A_0} H_E + 2H_{D_1} \left( H_{D_1} - H_{D_2} \right) \right]^{1/2} \]
MM-WAVE CHARACTERISTICS OF YTTRIUM ORTOFERRITE (YFeO₃)

Dielectric Parameters

<table>
<thead>
<tr>
<th></th>
<th>@ QFM-Mode</th>
<th>@ QAM-Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>εₓ'</td>
<td>23.2</td>
<td>25.4</td>
</tr>
<tr>
<td>εₓ''</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>εᵧ'</td>
<td>21.9</td>
<td></td>
</tr>
<tr>
<td>εᵧ''</td>
<td>0.09</td>
<td></td>
</tr>
</tbody>
</table>

*)AFMR – Antiferromagnetic Resonance (QFM Mode).

Transmission Spectrum of 1.21 mm Thick YFeO₃ Single Crystal in the External Magnetic Field H = 500 Oe.
AFMR PARAMETERS OF YFeO₃

Magnetic Tuning Coefficient: $\alpha = 0.7$ GHz/kOe

Frequency, GHz

Permeability

Extinction Coefficient

YFeO₃

$\Delta \mu = 0.27$

$\Delta \nu_{3dB} = 0.9$ GHz

$k_e = \varepsilon''\mu'/2n$

$k_m = \varepsilon\mu''/2n$

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SUMMARY

- It was demonstrated that the quasi-optical BWO spectroscopy is a powerful method allowing the comprehensive and accurate millimeter wave characterization of ferrites and antiferromagnets.

- The microwave loss in oriented hexaferrite ceramics depends strongly on conductivity and mutual orientation of the wave polarization ($e$-vector) and the axis of orientation ($A$). The experiments have revealed that in highly resistive materials the dielectric loss is higher in $e \parallel A$ polarization, while the microwave loss in conducting ceramics is higher in $e \perp A$ polarization.

- It was shown that the low dielectric loss and the noticeable declination of the mm-wave magnetic permeability from vacuum permeability make the non-collinear antiferromagnets promising for applications at the frequencies above 200 GHz.

- The confined-field circulator concept was described and the performance of the strip-line prototype was discussed. It was shown that the incorporation of soft and hard ferrites in one closed-loop ferrite assembly provides new opportunities for the microwave and mm-wave ferrite devices design.
REFERENCES


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