Agenda

- Waves in waveguides
- Standing waves and resonance
- Setup
- Experiment with microwave cavity
- Comments on Bragg diffraction experiment
Maxwell’s Equations

\[ \nabla \mathbf{D} = 0 \]
\[ \nabla \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]
\[ \nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \]

uniform plane wave traveling in \( z \)-direction \( \mathbf{H} \perp \mathbf{E} \)

wave equation

\[ \frac{\partial^2 \mathbf{E}_x}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 \mathbf{E}_x}{\partial t^2} \]

general form of solution

\[ \mathbf{E}_x(z, t) = f \left( t - \frac{z}{v} \right) + g \left( t + \frac{z}{v} \right) \]

propagation speed

\[ v = \frac{1}{\sqrt{\varepsilon \mu}} \]
\[ Z = \sqrt{\frac{\mu}{\varepsilon}} \]

\( \mathbf{E} \) vs \( \mathbf{H} \)

\[ \mathbf{E}_x = E_0 e^{i(\omega t - k z)} \]
\[ \mathbf{H}_y = \sqrt{\frac{\varepsilon}{\mu}} \mathbf{E}_x \]
\[ \mathbf{E}_x = Z \mathbf{H}_y \]
Wave Propagation in Wave Guides

\[ E_y = E_0 \sin k_x x \cdot e^{i(\omega t - k_z z)} \]
Standing Waves in Cavities

\[ E_y = E_0 \sin k_x x \cdot e^{i(\omega t - k_z)} \]

\[ + \]

\[ E_y = E_0 \sin k_x x \cdot e^{i(\omega t + k_z)} \]

= 

\[ L = n^* \lambda / 2 \]
Standing Waves in Cavities

\[ Ey = Ey(z) \]

\[ Ey = Ey(x \text{ or } z) \]
Resonances for transverse Electric Waves

\[ \omega_{mnp}^2 = v_0^2 \left[ \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2 + \left( \frac{p\pi}{c} \right)^2 \right] \]

-phase velocity

TE\textsubscript{101} mode: m=1, n=0, p=1

\[ \omega_{101}^2 = v_0^2 \pi^2 \left[ \left( \frac{1}{a} \right)^2 + \left( \frac{1}{c} \right)^2 \right] \]
Coupling between Wave Guide and Cavity

$Q_L = \frac{\omega L}{R + Z_0}$

$Q_L = \frac{\omega L}{Z_0 \left(1 + \frac{R}{Z_0}\right)} = \frac{Q_0}{(1 + \beta)}$

$\beta$: coupling coefficient

Maximum power transfer:

$Z_0 = R \Rightarrow \beta = 1$

$\Rightarrow Q_L = \frac{1}{2} Q_0$

$Q_0$ - quality factor without external load
Microwaves in Cavities. Overview of the Experiment.
Microwaves in Cavities. The Setup of the Experiment.
Use detector to find distance between minimums in the slotted line (wave guide)
Use detector to find distance between minimums in the slotted line (wave guide). Distance between consequent minima correspond $\lambda/2$. 

4/2/2018
Use plunger to change the dimension of the cavity in z-direction and search for maxima in power stored using the cavity detector. Identify $TE_{101}$ and $TE_{102}$.
Experiment. Cavity resonance.

\[ \omega_{102}^2 = v_0^2 \pi^2 \left[ \left( \frac{1}{a} \right)^2 + \left( \frac{2}{c} \right)^2 \right] \]

\[ f_{102} = \frac{v_0}{2} \sqrt{\left( \frac{1}{a} \right)^2 + \left( \frac{2}{c} \right)^2} \]

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<table>
<thead>
<tr>
<th>TE_{102}</th>
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<tbody>
<tr>
<td>( c_0 = 13.88 )</td>
</tr>
<tr>
<td>( c_1 = 13.86 )</td>
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<tr>
<td>( c_2 = 13.92 )</td>
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\[ I \text{ (mA)} \]

\[ I \text{ (cm)} \]

\[ Q = \frac{f_0}{\Delta f} \sim 450 \]

\[ f \text{ (GHz)} \]
By moving the plunger we changing the resonance frequency of the cavity.
Experiment. Cavity resonance. Oscillator tuning.
1. Oscilloscope should run in X-Y mode
2. To plot the I(f) dependence you have to download both Ch1 and Ch2 data
3. Use triangular waveform as a voltage applied to modulation input of the oscillator
4. Use a proper time scale setting on the scope which could estimated from scanning frequency
5. Apply the calibration equation to calculate the frequency of the oscillator from the modulation voltage

\[ f = 0.03706 \cdot V_{\text{mod}} + 2.9349 \]
Experiment. Cavity resonance. Oscillator tuning.

Voltage tunable oscillator ZX95-3250a-S+ from Mini-Circuits®
FM Calibration for microwave oscillator

**Equation**
\[ y = \frac{B_1 x^4 + B_2 x^2}{2} + \text{Intercept} \]

**Weight**
No Weighting

**Residual Sum of Squares**
8.01482E-5

**Adj. R-Square**
0.99977

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<thead>
<tr>
<th>Frequency</th>
<th>Value</th>
<th>Standard Error</th>
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<tr>
<td>Intercept</td>
<td>2.91874</td>
<td>8.0905E-4</td>
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<tr>
<td>B1</td>
<td>0.03588</td>
<td>3.43148E-4</td>
</tr>
<tr>
<td>B2</td>
<td>-4.41E-5</td>
<td>3.20212E-5</td>
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**Graph**

The graph shows the relationship between **f (GHz)** and **V_Tune IN (V)** for the ZX95-3250a-S+ microwave oscillator, illustrating the FM calibration curve.
Experiment. Cavity resonance.

![Graph showing cavity resonance with Q=340 and Q=133, labeled as TE101.](image-url)
By changing the coupling between oscillator and cavity we can control the quality factor of the cavity resonance but in the same time we changing the power delivered to the cavity.
Experiment. Coupling: Detecting of the Magnetic field.

While in resonance: turn orientation of the input loop from the vertical direction in 10° steps to 360°. Read cavity detector.
Experiment. Coupling: Detecting of the Magnetic field.

Experimental result. Fitted to
\[ A|\cos(\alpha + \phi)|^n + A_0 \]
Presence of dielectric reduces length of cavity at a given resonance frequency $\omega_0$.
This effect grows with the electric field strength $E_y$.

(0) Without dielectric the cavity length at resonance is $c_0$.
(1) Place dielectric into cavity and move in 0.5cm steps, $l_i$.
(2) At each place tune plunger to resonance and record $c_i$.
(3) Plot $\Delta c_i = |c_0 - c_i|$ versus $l_i$: this measures now $E_y$ vs $l_i$. 

Electric Field Distribution.
Electric Field Distribution.

**Electric field distribution**

$TE_{102}$ mode

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<th>cavity retune (cm)</th>
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<th>10</th>
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**Courtesy of P. Debevec**
Quality factor ($\text{TE}_{101}$ mode) of unloaded cavity can be calculated as:

$$Q_0 = \frac{abc \left( a^2 + c^2 \right)}{\delta \left[ 2b \left( a^3 + c^3 \right) + ac \left( a^2 + c^2 \right) \right]}$$

$\delta$ is the skin depth at frequency $\omega_0$

$$\delta = \sqrt{\frac{2\rho}{\mu \omega}}$$

$\rho$ – resistivity of the cavity material

$\mu = \mu_r \mu_0 \approx \mu_0 = 4\pi \times 10^{-7}$
Calculation of the Quality factor of the Unloaded Cavity

For red brass \( \rho = 6 \times 10^{-8} \Omega \text{m} \)
\( \mu \approx 4\pi \times 10^{-7} \)
\( \delta = 2.25 \times 10^{-6} \text{m} \)

\[ Q_0 = \frac{abc \left( a^2 + c^2 \right)}{\delta \left[ 2b \left( a^3 + c^3 \right) + ac \left( a^2 + c^2 \right) \right]} \]

\( a = 7.22 \text{ cm}, \ b = 3.42 \text{ cm}, \ c = 6.91 \text{ cm} \ (\text{TE}_{101}) \)

\( \delta = \sqrt{2 \rho / \mu \omega} \)

\( Q_0 \approx 7700 \)
Bragg diffraction.

\[ n\lambda = 2d \sin \theta \]  
\textit{Bragg's Law}

\[ \theta' = 90^\circ - \theta \]
Bragg diffraction. Results.*

Matthew Stupca
Longxiang Zhang
Bragg diffraction. Possible origin of the $\sim 10^\circ$ peak

Second order reflection

Lloyd's mirror effect