THz source based on the electron beam-semiconductor interaction

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NSRRC
Taiwan Light Source
<table>
<thead>
<tr>
<th></th>
<th>TLS (operational since 1993)</th>
<th>TPS (under development)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy (GeV)</strong></td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td><strong>Beam Current (mA)</strong></td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td><strong>Bunch length (mm)</strong></td>
<td>9.2</td>
<td>2.86</td>
</tr>
<tr>
<td><strong>Emittance (nm-rad)</strong></td>
<td>25</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Circumference (m)</strong></td>
<td>120</td>
<td>518.4</td>
</tr>
</tbody>
</table>

**NSRRC**
Plasma definition

Gaseous plasma
- Free electrons
+ Mobile ions

Plasma in metals
- Free electrons
+ Immobile ions

Plasma in semiconductors
+ Mobile holes
- Free electrons
- Immobile dopant ions


Plasma parameters

[A.L. Peratt, Astrophysics and Space Science 242, 93 (1997)]
THz frequency range

Schematic diagram of the electromagnetic spectrum

[O.P. Williams, Reports on Progress in Physics 69, 301 (2006)]
Plasma based THz sources

Excitation of THz radiation from a laser-plasma interaction.

Generation of transition radiation at plasma-vacuum boundary by an electron bunch.
Plasma based THz sources

- Generation of Cherenkov radiation by an electron bunch.
- Excitation of charge-density waves as a result of electron beam-plasma interaction.
Formulation of the problem

Studied plasma waveguide.

- Semiconductor plates
- Perfect conductor
- Vacuum
- Electron beam

H
Formulation of the problem

System of equations

- Maxwell’s equations
- Equations of motion
- Continuity equations
- Boundary conditions

Dispersion equation

\[ f(\omega_p, \Omega_H, \nu, v_0, \vec{H}_0, \text{geometry}, \omega, k) = 0 \]
Numerical results: $\vec{H}_0 = 0$

Symmetrical case.

Field distribution for Hz-component of LM-wave.

Antisymmetrical case.
Numerical results

\[ A(\vec{r}, t) \sim \exp[-i\omega t] \]
Numerical results: $\vec{H}_0 = 0$

Spectrum of *bulk* and *surface* LM-waves electromagnetic waves in the plasma waveguide.

$\nu = 0$  
$\nu \neq 0$
Numerical results: $\vec{H}_0 = 0$

**Spectrum of surface electrostatic waves.**

**Growth rates of the space-charge waves.**
Numerical results: $\vec{H}_0 \neq 0$

Spectrum of *bulk* and *surface* electrostatic waves in the plasma waveguide.
Numerical results: $\vec{H}_0 \neq 0$

Schematic diagram of the beam-plasma interaction.
Numerical results: $\vec{H}_0 \neq 0$

Growth rates of the Van Kampen waves and cyclotron waves.
Numerical results: $\vec{H}_0 \neq 0$

Growth rates of the Van Kampen waves as a function of volume mode number.

Growth rates of the Van Kampen waves as a function of volume mode number.
Numerical results: $\vec{H}_0 \neq 0$

Growth rates of the Van Kampen waves and cyclotron waves as functions of external magnetic field strength.

Growth rates of the Van Kampen waves and cyclotron waves as functions of collision frequency of electrons.
Formulation of the problem

Studied plasma waveguide.
Numerical results: $\vec{H}_0 = 0$

Growth rate of the space-charge wave.

Maximum growth rate as function of the azimuthal wave number.
Numerical results: $\vec{H}_0 \neq 0$

Growth rates of the Van Kampen waves and cyclotron waves.

Maximum growth rate of the Van Kampen waves as function of the azimuthal wave number.
Numerical results: $\vec{H}_0 \neq 0$

Growth rates of the Van Kampen waves and cyclotron waves as functions of external magnetic field strength.

Growth rates of the Van Kampen waves and cyclotron waves as functions of collision frequency of electrons.
Formulation of the problem

Studied plasma waveguide.
Numerical results

Growth rates of the space-charge waves.

\[ \gamma/\omega_n \]

\[ ck_z/\omega_n \]
Experimental studies

The structure of the experimental unit.

[O. A. Zamuraev, I. V. Lopatin and A. F. Rusanov, Telecommunications and Radio Engineering 64, 841 (2005)]
Experimental studies

- $E_b = 6\text{keV}$
- $j_b = 150\text{A/cm}^2$
- $\tau_b = 1\text{ms @ 40Hz}$
- $f_{exc} = 70\text{GHz} = f_p/1.8$
- $H_0 = 0.04 \div 0.26T$
- $T = -196 \div -190^\circ C$

Observed amplification of the input power.
Conclusion

- Instability can occur in the wide frequency range;
- Growth rates peak under the resonance conditions;
- Magnetic field and electron collisions stabilize the instability;
- Excitation of electromagnetic waves at frequencies about 0.1 THz was demonstrated as a result of interaction between a 6-keV electron beam with semiconductor plasma.

Collaborators

- Prof. Vladimir Yakovenko (Theory)
- Dr. Igor Lopatin (Experiment)
- Ph.D. Student Oleg Zamuraev (Experiment)
Formulation of the problem

Cartesian coordinates, $\vec{H}_0 = 0$, no beam
Formulation of the problem

Maxwell’s equations

\[ \nabla \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{H}}{\partial t}, \quad \nabla \times \vec{H} = \frac{1}{c} \frac{\partial \vec{D}}{\partial t}, \]
\[ \nabla \cdot \vec{D} = 0, \quad \nabla \cdot \vec{H} = 0. \]  

Field dependence on the coordinates and time

\[ \vec{A}(\vec{r}, t) = \vec{A}(x, y) \exp [i(k_z z - \omega t)]. \]
Formulation of the problem

Electric displacement

\[ \vec{D}(\omega) = \epsilon(\omega) \vec{E}(\omega). \] (3)

Permittivity of the semiconductor plasma

\[ \epsilon(\omega) = \epsilon_s(\omega) = \epsilon_0 \left( 1 - \frac{\omega_p^2}{\omega (\omega + i\nu)} \right), \] (4)

where \( \omega_p^2 = \omega_0^2 \epsilon_0 = 4\pi e^2 N_0 / m^* \) — plasma frequency.
Formulation of the problem

**EM field in a layered rectangular waveguide**

\[ \text{EM Field} = \text{LE-wave} (E_y = 0) + \text{LM-wave} (H_y = 0) \]

**Boundary conditions**

Plasma-metal interface:

\[ E_{s||} = 0, \quad H_{s\perp} = 0. \]  \hspace{1cm} (5)

Plasma-vacuum interface:

\[ E_{s||} - E_{d||} = 0, \quad H_{s||} - H_{d||} = 0. \]  \hspace{1cm} (6)
Dispersion equation

\[
F_1^{LE} F_2^{LE} = 0, \quad (7)
\]

\[
F_1^{LM} F_2^{LM} = 0. \quad (8)
\]

\[
F_1^{LE} = \frac{k_y d}{k_y s} \tan(k_y s b_1) + \tan(k_y d b_2),
\]

\[
F_2^{LE} = \frac{k_y s}{k_y d} \tan(k_y s b_1) - \tan(k_y d b_2),
\]

\[
F_1^{LM} = \frac{k_y s}{\varepsilon_s} \tan(k_y s b_1) + \frac{k_y d}{\varepsilon_d} \tan(k_y d b_2),
\]

\[
F_2^{LM} = \frac{k_y s}{\varepsilon_s} \tan(k_y s b_1) - \frac{k_y d}{\varepsilon_d} / \tan(k_y d b_2),
\]

\[
k_y s = \sqrt{-k_x^2 - k_z^2 + \omega^2 \varepsilon_s / c^2}, \quad k_y d = \sqrt{-k_x^2 - k_z^2 + \omega^2 \varepsilon_d / c^2},
\]

\[
k_x = n \pi / a, \text{ where } n = 1, 2, \ldots
\]
Formulation of the problem

Cartesian coordinates, $\vec{H}_0 || z$, with beam

[Diagram showing a Cartesian coordinate system with labels for semiconductor, plasma, perfect conductor, and vacuum regions.]
Formulation of the problem

System of equations

Maxwell’s equations (the speed of light $c \rightarrow \infty$)

$$\nabla \times \vec{E} = 0, \nabla \cdot \vec{D} = 0.$$(9)

Electric displacement

$$\vec{D} = \varepsilon \vec{E} + 4\pi \int_{-\infty}^{t} \vec{j}(t')dt'.$$(10)

Field dependence on the coordinates and time

$$\vec{A}(r, t) = \vec{A}(x, y)\exp [i(k_zz - \omega t)].$$ (11)
Formulation of the problem

Electron beam region \((\epsilon = \epsilon_d)\)

\[
\vec{j} = \vec{j}_b = en_0 \vec{v} + en \vec{v}_0, \quad (12)
\]

\[
\text{div} \vec{j}_b = -e \frac{\partial n}{\partial t}, \quad (13)
\]

\[
\frac{\partial \vec{V}}{\partial t} + \nu_0 \frac{\partial \vec{V}}{\partial z} = \frac{e}{m} \vec{E} + [\vec{V}, \vec{\omega}_H]. \quad (14)
\]

Semiconductor plates \((\epsilon = \epsilon_0)\)

\[
\vec{j} = \vec{j}_s = eN_0 \vec{V}, \quad (15)
\]

\[
\frac{\partial \vec{V}}{\partial t} + \nu \vec{V} = \frac{e}{m^*} \vec{E} + [\vec{V}, \vec{\Omega}_H]. \quad (16)
\]
Formulation of the problem

Electric displacement in the beam

\[ D_{ib} = \hat{\epsilon}_{ikb} E_{kb} \quad (i, k = x, y, z). \] (17)

Nonzero elements of the dielectric tensor \( \hat{\epsilon}_{ikb} \)

\[
\begin{align*}
\epsilon_{xxb} &= \epsilon_{yyb} = \epsilon_d + \frac{\omega_b^2 (\omega - k_z v_0)}{\omega \left( \omega^2_H - (\omega - k_z v_0)^2 \right)}, \\
\epsilon_{xyb} &= -\epsilon_{yxb} = \frac{\omega_b^2}{\omega \left( \omega^2_H - (\omega - k_z v_0)^2 \right)}, \\
\epsilon_{zxb} E_x &= \frac{-\omega_b^2 v_0}{\omega (\omega - k_z v_0) \left[ \omega^2_H - (\omega - k_z v_0)^2 \right]} \left\{ (\omega - k_z v_0) \frac{\partial E_x}{\partial x} + \frac{\omega_H}{n_0} \frac{\partial (n_0 E_x)}{\partial y} \right\}, \\
\epsilon_{zyb} E_y &= \frac{\omega_b^2 v_0}{\omega (\omega - k_z v_0) \left[ \omega^2_H - (\omega - k_z v_0)^2 \right]} \left\{ \omega_H^2 \frac{\partial E_y}{\partial x} - \frac{(\omega - k_z v_0)}{n_0} \frac{\partial (n_0 E_y)}{\partial y} \right\}, \\
\epsilon_{zzb} &= \epsilon_d - \frac{\omega_b^2}{(\omega - k_z v_0)^2}.
\end{align*}
\] (18)
Formulation of the problem

Electric displacement in the semiconductor

\[ D_{is} = \hat{\epsilon}_{iks} E_{ks} \ (i, k = x, y, z). \]  

(19)

Nonzero elements of the dielectric tensor \( \hat{\epsilon}_{iks} \)

\[ \epsilon_{xxs} = \epsilon_{yys} = \epsilon_0 + \frac{\omega_0^2 (\omega + \nu)}{\omega \left[ \Omega_H^2 - (\omega + \nu)^2 \right]}, \]
\[ \epsilon_{xys} = -\epsilon_{yxs} = \frac{\omega_0^2 \Omega_H}{\omega^2 \Omega_H} \]
\[ \epsilon_{zzs} = \epsilon_0 - \frac{\omega_0^2}{\omega(\omega + \nu)}. \]  

(20)
Boundary conditions

In each region of the plasma waveguide

\[
\Delta_\perp E_{z\mu} + k_{\perp\mu}^2 E_{z\mu}(x, y) = 0,
\]

(21)

where

\[
\Delta_\perp = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}, \quad k_{\perp\mu}^2 = k_x^2 + k_{y\mu}^2.
\]

Relations between the components of the vector \( \vec{E} \)

\[
E_{x\mu}(x, y) = -\frac{i}{k_z} \frac{\partial E_{z\mu}(x, y)}{\partial x}, \quad E_{y\mu}(x, y) = -\frac{i}{k_z} \frac{\partial E_{z\mu}(x, y)}{\partial y}.
\]

(22)
Boundary conditions

Using the boundary conditions on metal, we get

\[ E_{zs}(x, y) = A \frac{\sin k_{ys}(b+y)}{\sin k_{ys}b} \exp (ik_x x), \quad -b < y < -b_1; \]
\[ E_{zb}(x, y) = (B \cos k_{yb} y + C \sin k_{yb} y) \exp (ik_x x), \quad -b_1 < y < b_2; \]  
\[ E_{zs}(x, y) = D \frac{\sin k_{ys}(b-y)}{\sin k_{ys}b} \exp (ik_x x), \quad b_2 < y < b, \]  

(23)

where

\[ k_{yb}^2 = -k_x^2 - k_z^2 \frac{\epsilon_{zzb}}{\epsilon_{yyb} + \omega^2 k_z v_0 - \omega \left[ \omega_H - (\omega - k_z v_0)^2 \right]} , \]

\[ k_{ys}^2 = -k_x^2 - k_z^2 \frac{\epsilon_{zzs}}{\epsilon_{yys}} , \]

\[ k_x^2 = \left( \frac{l \pi}{a} \right)^2, \quad l = 0, 1, 2, \ldots \]
Boundary conditions

Boundary conditions for the component $E_z$

Plasma-metal interface:

$$E_{zs} = 0.$$  \hspace{1cm} (24)

Beam-plasma interface:

$$E_{zb} (y) - E_{zs} (y) = 0.$$ \hspace{1cm} (25)
Boundary conditions

Boundary conditions for the component $D_y$

Beam-plasma interface:

$$\int_{y-\delta/2}^{y+\delta/2} \text{div} \mathbf{D}(y) dy = 0.$$  \hspace{1cm} (26)

For $y = b_2$ the above equation takes the form:

$$D_{yb} (y) - D_{ys} (y) = \frac{\omega_b^2 k_z v_0}{\omega [\omega_p^2 - (\omega - k_z v_0)^2]} \times \left\{ \frac{\omega_H}{(\omega - k_z v_0)} E_{xb} (\pm b_2) - E_{yb} (\pm b_2) \right\}. \hspace{1cm} (27)$$
Dispersion equation

\[
\left( k_{yb}^2 g_2^2 - k_x^2 (\epsilon_{yxs} + g_1)^2 \right) \sin k_{ys}(b - b_1) \sin k_{ys}(b - b_2) \times \\
\times \sin k_{yb}(b_1 + b_2) - \\
- k_{ys}^2 \epsilon_{yys}^2 \cos k_{ys}(b - b_1) \cos k_{ys}(b - b_2) \sin k_{yb}(b_1 + b_2) + \\
+ k_{ys} \epsilon_{yys} \cos k_{ys}(b - b_1) \sin k_{ys}(b - b_2) \times \\
\times (ik_x (\epsilon_{yxs} + g_1) \sin k_{yb}(b_1 + b_2) + k_{yb} g_2 \cos k_{yb}(b_1 + b_2)) + \\
+ k_{ys} \epsilon_{yys} \sin k_{ys}(b - b_1) \cos k_{ys}(b - b_2) \times \\
\times (k_{yb} g_2 \cos k_{yb}(b_1 + b_2) - ik_x (\epsilon_{yxs} + g_1) \sin k_{yb}(b_1 + b_2)) = 0,
\]

where \( g_1 = i \frac{\omega_b^2 \omega H k_z v_0}{\omega(\omega - k_z v_0)[\omega_H^2 - (\omega - k_z v_0)^2]} - \epsilon_{yxb}, \)

\[
g_2 = \frac{-\omega_b^2 k_z v_0}{\omega[\omega_H^2 - (\omega - k_z v_0)^2]} - \epsilon_{yyb}.
\]