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Stimulated Cherenkov emission in carbon nanotubes

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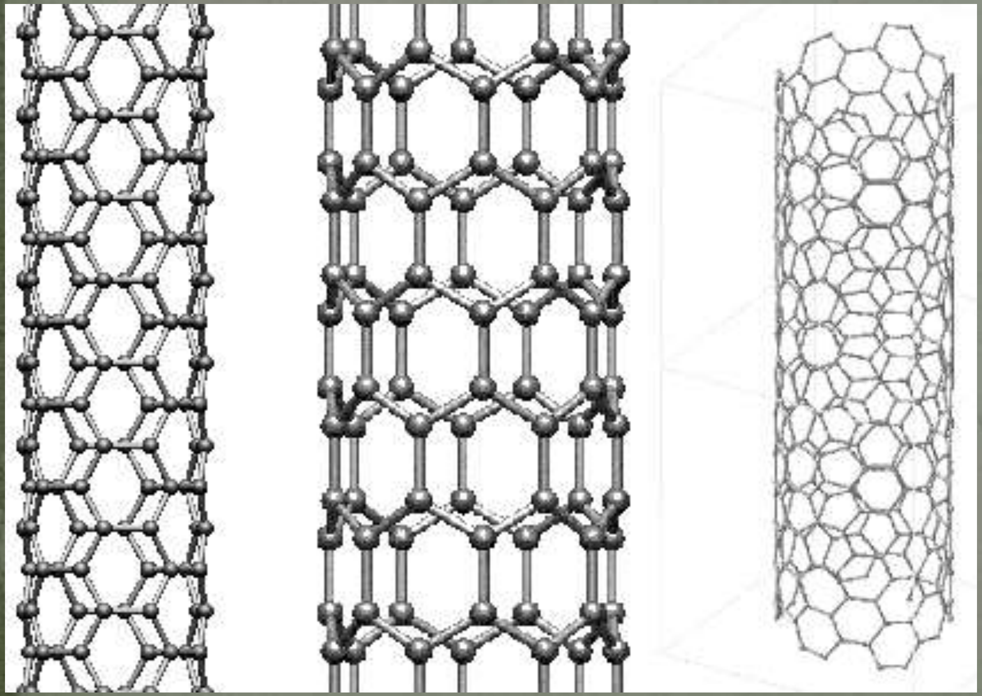
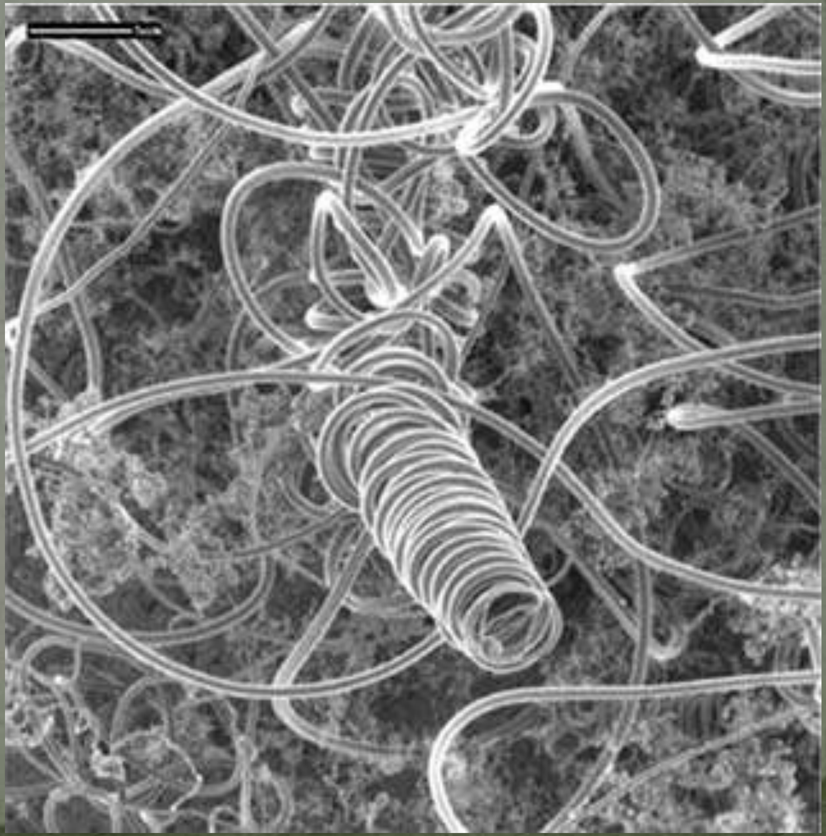
Motivation:

- THz frequencies characterize different important physical processes (rotation of small molecules, collective vibration modes of proteins, typical superconducting energy gaps, oscillations in gaseous and solid-state plasmas etc.)

- Reliable THz devices are required for air pollution monitoring, poison gas sensing, DNA manipulation, gene diagnostics and other applications

One of the latest trends is to use single-wall carbon nanotubes (SWNTs) — cylindrical molecules with nanometer diameter and micrometer length — as building blocks of novel THz devices.





Basic properties of carbon nanotubes (CNT):

- ballisticity of the electron flow over typical CNT length (about 10 microns)
  (S. Frank at al. "Carbon nanotube quantum resistors," *Science* **280**, 1744 (1998), C. Berger at al. "Multiwalled carbon nanotubes are ballistic conductors at room temperature," *Appl. Phys. A* **74**, 363–365 (2002)),
- extremely high current-carrying capacity (10^9 – 10^{10} A/cm^2)
  (Z. Yao at al. "High-field electrical transport in single-wall carbon nanotubes," *Phys. Rev. Lett.* **84**, 2941–2944 (2000), B. Q.Wei, at al. "Reliability and current carrying capacity of carbon nanotubes," *Appl. Phys. Lett.* **79**, 1172 (2001),
- strong slowing down of surface electromagnetic waves (50-100 times)
  (G. Y. Slepyan at al. "Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation," *Phys. Rev. B* **60**, 17136–17149 (1999), S. A. Maksimenko and G. Y. Slepyan, *The Handbook of Nanotechnology: Nanometer Structure Theory, Modeling, and Simulation*, SPIE Press, Belingham (2004)).

Goals and tasks:

- The mechanism of stimulated emission of electromagnetic radiation by an electron beam in carbon nanotubes must be theoretically considered.
- The dispersion equation must be obtained, the threshold generation conditions must be analyzed.

Interaction between electron beam and produced electromagnetic wave leads to electron beam modulation. This process can be described by self-consistent system for electromagnetic field:

$$\nabla\left(\nabla\cdot\mathbf{E}(\mathbf{r},\omega)\right)-\Delta\mathbf{E}(\mathbf{r},\omega)=\frac{4\pi i\omega}{c^2}\mathbf{j}(\mathbf{r},\omega)$$

and for electrons:

$$i\frac{\partial\psi}{\partial t}=H\psi$$

$$\mathbf{j}(\mathbf{r},t)=\frac{e}{2m}\left\{\psi^*(\mathbf{r},t)\mathbf{p}\psi(\mathbf{r},t)-(\mathbf{p}\psi^*(\mathbf{r},t))\psi(\mathbf{r},t)\right\}-\frac{e^2}{mc}\left|\psi(\mathbf{r},t)\right|^2\mathbf{A}(\mathbf{r},t).$$

Dispersion equation for electromagnetic wave coupled with electron beam :

$$k - k_m = -\frac{\omega_L^2}{8k_m m_e c^2}\sum_l \left|B_{nl}^{(m)}\right|^2 \times$$

$$\times\left[\frac{1}{-\hbar\omega + \varepsilon_n(p_n) - \varepsilon_l(p_n - k)} + \frac{1}{\hbar\omega + \varepsilon_n(p_n) - \varepsilon_l(p_n + k)}\right]$$

Emission of photons

Absorption of photons

Classical limit:

$$k - k_m = k^2 \frac{\partial^2 \varepsilon_s}{\partial p_n^2} \frac{b_{ns}^{(m)}}{(\omega - k v_s)^2}$$

Quantum limit:

$$k - k_m = \frac{b_{nn}^{(m)}}{\hbar} \frac{1}{\omega - v_s k - \frac{\hbar}{2} \frac{\partial^2 \varepsilon_n}{\partial p_n^2} k^2}$$

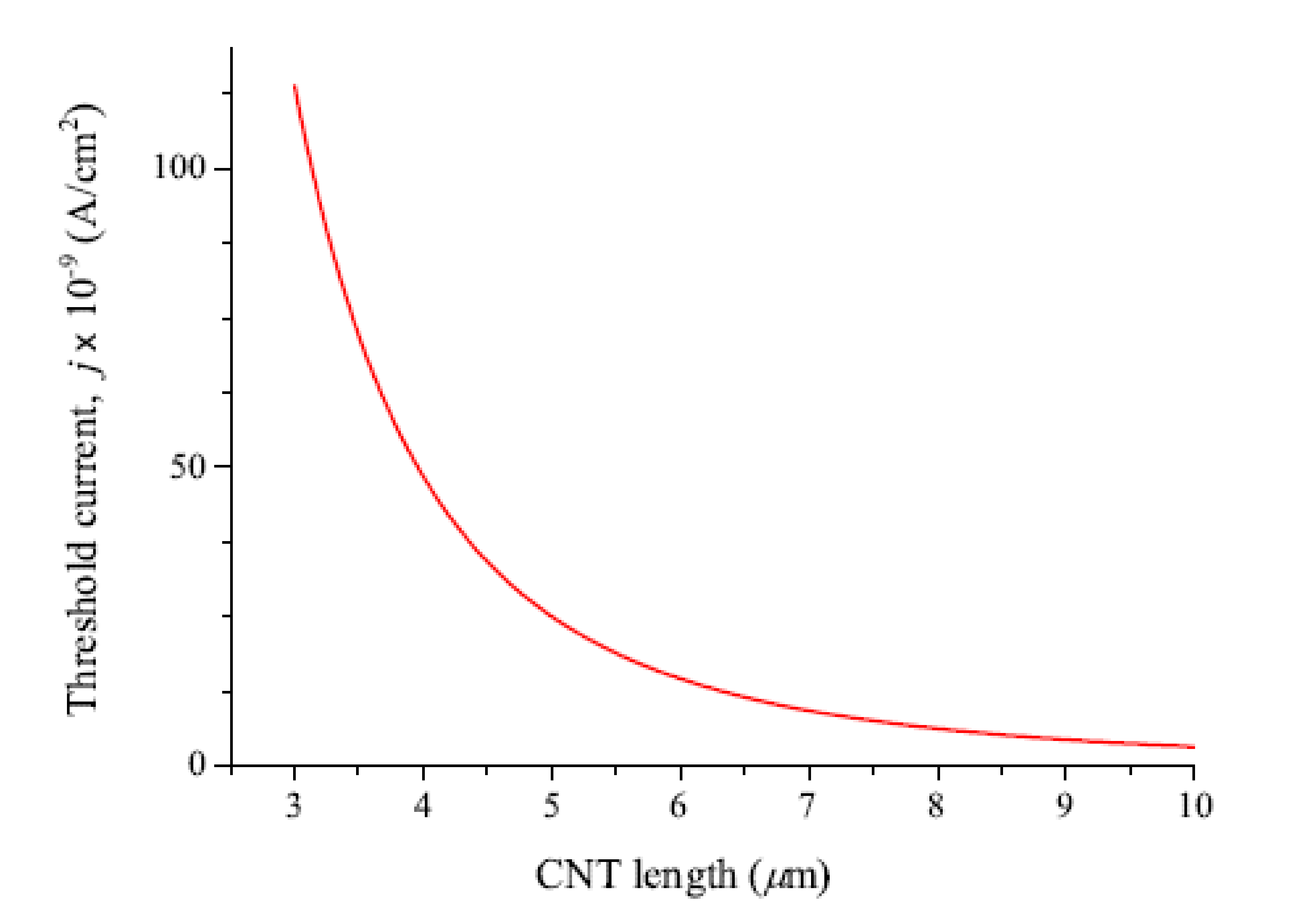


Fig. 1. The dependence of threshold current density on nanotube length.

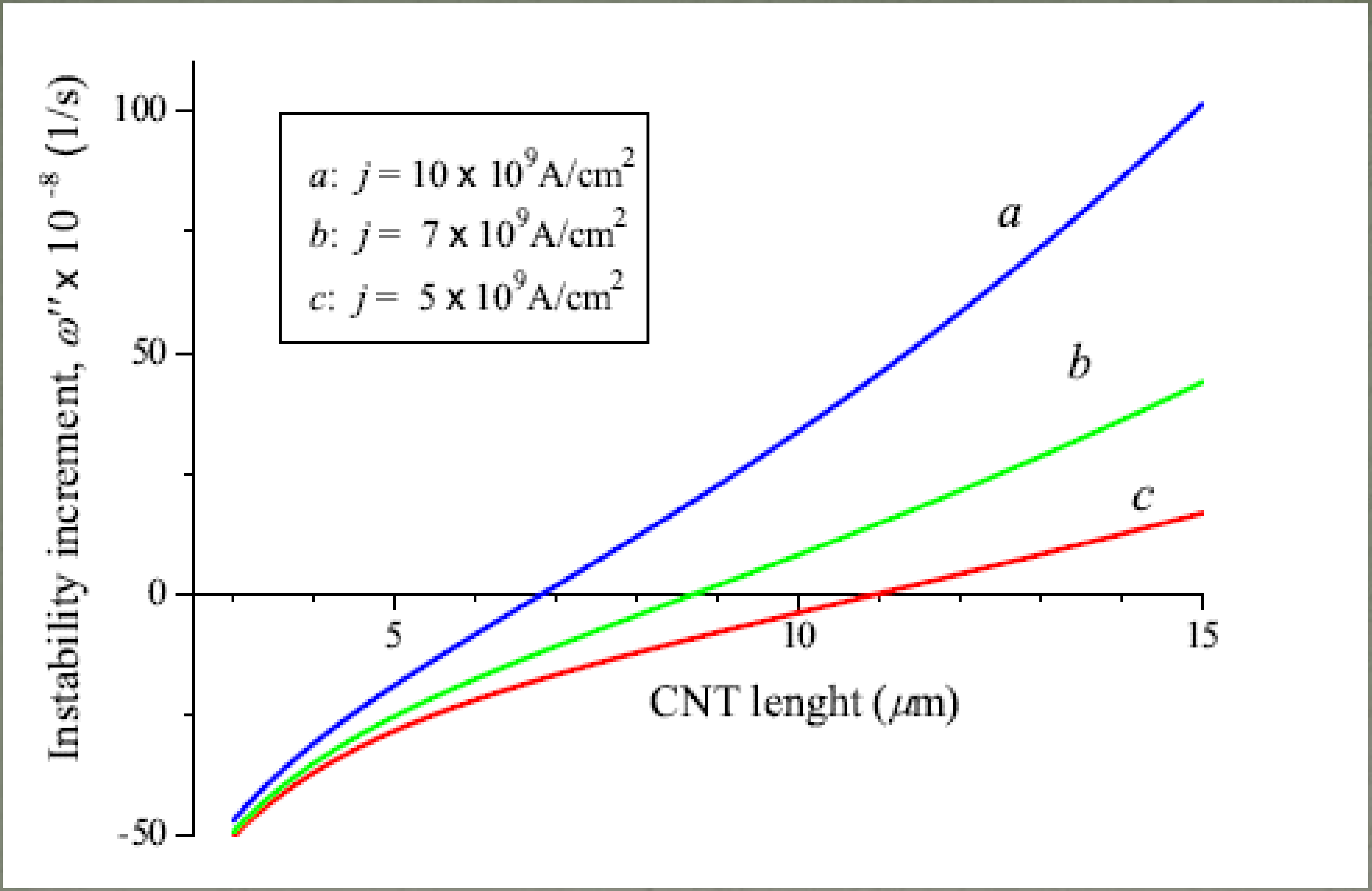


Fig. 2. Instability increment *vs* nanotube length at different electron current densities.

Conclusion:

- The mechanism of stimulated emission of electromagnetic radiation by an electron beam in carbon nanotubes is theoretically considered.
- The dispersion equations are obtained and the threshold generation conditions are analyzed.
- It is shown the realizability of the nanotube-based Cherenkov-type emitters at realistic parameters of electronic currents densities in nanotube and nanotube length ~ 10 μm.

Thank you for attention!