Sapphire decelerating capillary channel integrated with antenna at frequency 0.675 THz

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Abstract. In recent years, there has been an increasing interest in THz-radiation for application in medicine (THz tomographs), in pharmaceutics (composition analysis for medicines), in introscopy of large-scale objects (ships, trains, containers) and others. THz-radiation can be generated by relativistic electron bunches passing through the Cherenkov decelerating capillary channel (circular waveguide with dielectric filling) with horn extraction. Relativistic electron beams having ~100 μm in diameter and pulse durations of 1 ps or less (as in photoinjectors) are capable of producing substantial power of THz-radiation. High-peak power coherent Cherenkov radiation can be produced by a properly modulated high-brightness electron beam or by a single, high-density bunch having sub-wavelength dimension. The aperture of a Cherenkov decelerating structure should be comparable with the mm or sub-mm wavelength (0.1-3 mm). Different dielectric materials for the internal surface coating of the capillary channel of mm-sub-mm cross-section can be used. As is known, a frequency of 0.675 THz corresponds to the atmospheric window with high transparency. This report presents the results of electrodynamics study of the metallized sapphire decelerating Cherenkov capillary. A horn antenna attached to the metallized sapphire capillary channel at the 0.675 THz resonant frequency will be considered.

1. Introduction
THz-frequency range radiation sources are necessary for huge variety of applications. Many types of THz radiation generation principles are known: orotrons, TWT’s, nonlinear convertors based on semiconductors or gas filled tubes, gyrotrons [1]. But only large scale facilities such as FEL’s can generate coherent THz radiation. The other possible method of coherent THz-radiation generation is based on high brightness relativistic electron bunches passing through the Cherenkov decelerating capillary channel (circular waveguide with dielectric filling) or the corrugating channel with horn extraction [2]. Relativistic electron beams having ~100 μm in diameter and pulse durations of 1 ps or less (as in photoinjectors) are capable of producing substantial power of THz radiation.

Besides THz radiation generation, the problem of transportation and output of so powerful radiation into the atmosphere is not less difficult to develop such structures. The aperture of a Cherenkov decelerating structure should be comparable with the mm or sub-mm wavelength (0.1-3 mm). Different dielectric materials for the internal surface coating of the capillary channel of mm or sub-mm cross-section can be used. This paper describes estimation for electrodynamical characteristics of a decelerating capillary structure without radiation power estimation.

THz radiation in a broad band of frequencies possesses low penetration because of its high absorption in water. Based on data obtained in the observatory of Mauna Kea for THz radiation
transmission in atmosphere, transmission windows are defined in ranges of frequencies 0.6-0.7; 0.8-0.98 THz and some over [3].

A frequency of 0.675 THz corresponds to the atmospheric window with high transparency and was chosen for the simulation. This paper presents the results of electrodynamics study of the metallized sapphire decelerating Cherenkov capillary. A horn antenna attached to such capillary channel at the 0.675 THz resonant frequency will be considered.

2. Geometrical and electrodynamical characteristics of dielectric loaded capillary
CST Microwave Studio was used for simulation of a decelerating capillary structure with dielectric filling [4]. Sapphire was chosen as a material of dielectric filling, because it has high durability, dielectric constant $\varepsilon \sim 9.9$, thermal stability up to 1600 °C and there is almost no heat conductivity. The electrodynamical model of a decelerating sapphire capillary structure at a resonance frequency of 0.675 THz is shown in the figure 1. Geometrical and electrodynamics characteristics of the decelerating capillary channel with sapphire coating at a resonance frequency of 0.675 THz are presented in tables 1 and 2.

![Electrodynamical model (front view) of a decelerating sapphire capillary structure at a resonance frequency of 0.675 THz. 1 – vacuum; 2 – dielectric coat; $D_{\text{cap}}$ – capillary diameter; $D_{\text{diel}}$ – dielectric coat thickness.](image)

**Figure 1.** Electrodynamical model (front view) of a decelerating sapphire capillary structure at a resonance frequency of 0.675 THz. 1 – vacuum; 2 – dielectric coat; $D_{\text{cap}}$ – capillary diameter; $D_{\text{diel}}$ – dielectric coat thickness.

**Table 1.** Geometrical characteristics of the decelerating capillary channel with sapphire coating at a resonance frequency of 0.675 GHz.

| Diameter of vacuum channel $D_{\text{vac}}$ (µm) | Dielectric coat thickness $D_{\text{diel}}$ (µm) | Structure diameter $D_{\text{cap}}$ (µm) | Structure length $L_{\text{cap}}$ (mm) |
|-----------------------------------------------|-----------------------------------------------|----------------------------------------|---------------------------------------|
| 312.6                                         | 24.8                                          | 337.4                                  | 0.5                                   |

**Table 2.** Electrodynamical characteristics of the decelerating capillary channel with sapphire coating at a resonance frequency of 0.675 GHz.

| Material    | $\varepsilon$ | $Q$-factor | $R_{\text{sh}}$ (MOhm/m) | $R_{\text{sh}}/Q$ (Ohm/m) | $\beta_{\text{group}}$ | Resonant frequency $F$ (THz) |
|-------------|---------------|------------|---------------------------|---------------------------|------------------------|------------------------------|
| Sapphire    | 9.9           | 1531       | 50.17                     | 32.77                     | 0.43                   | 0.675                        |
3. The radiating horn antenna integrated with the capillary channel

It is necessary to match a radiation source output with an open space for more efficient THz radiation. There is a need to obtain an effective matching of the Cherenkov capillary with an open space, as well as to provide the necessary directivity. The capillary channel radiated by the open end does not provide the high directivity of radiation. It can be seen from the diagrams shown in the figure 2. Furthermore, the reflection of the wave from the open end will be observed. The reflection coefficient of the open end is equal to -10.1 dB for the capillary having parameters which are given in tables 1 and 2. Higher radiation bands are far from the operating frequency and the next ones have a resonant frequency of 0.885 THz, which differs by 30% from the chosen frequency and the width of this band is 0.031 THz (3.5%), the reflection coefficient is equal to -21.6 dB.

**Figure 2.** Circular (a) and three-dimensional (b) patterns of the decelerating sapphire capillary at an operating frequency of 0.675 THz without the extractor.

An antenna must be used for increasing the radiation efficiency. The capillary has a circular cross section, therefore it is clear that the solution will be a horn antenna which will be directly attached to the end of a capillary structure. The main parameters of the antenna are directivity, angle between the axis of the antenna and direction of the main lobe, angular width of the main lobe and reflection coefficient of the horn, radiation reflectivity from the horn and width of the operating frequency band.

Further electrodynamics model of the copper antenna matched with the sapphire capillary was tuned to a resonant frequency of 0.675 THz (figure 3). Geometrical characteristics and simulation results of the radiating horn matching with the decelerating sapphire capillary channel are presented in the table 3. Directivity patterns of such extractor and variation characteristics are shown in the figure 4. The length of horn was varied to achieve the optimal directivity. Then the horn aperture angle was varied at the obtained fixed length of horn L = 0.168 mm. The S-parameter’s analysis results are shown in the figure 5. Here the S11-parameter is interpreted as a wave reflection coefficient from the output side into a horn antenna.

**Table 3.** Geometrical characteristics of the radiating horn and matching simulation results of the decelerating sapphire with copper capillary tuned at a frequency of 0.675 THz (parameters are shown in figure 3).

| $D_{cap}$ (μm) | $D_{dil}$ (μm) | $D_{met}$ (μm) | $D_{capmet}$ (μm) | $D_{rup}$ (μm) | $L_{cap}$ (mm) | $L_{caphorn}$ (mm) | Directivity (dB) | Angular width (°) | Reflectivity (dB) | Operating frequency band width (THz (%)) |
|----------------|---------------|--------------|------------------|--------------|---------------|------------------|-----------------|-----------------|-----------------|-------------------------------------|
| 60             | 24.9          | 49.6         | 334.5            | 480          | 0.3           | 0.468            | 9.94            | 57.8            | -33.52          | 0.031 (4.6)          |
**Figure 3.** Electrodynamic model of the circular horn matched with the decelerating channel: 1 – vacuum; 2 – dielectric coat; 3 – copper; $D_{\text{cap}}$ – diameter of vacuum channel; $D_{\text{diet}}$ – dielectric coat thickness; $D_{\text{met}}$ – copper thickness; $D_{\text{capmet}}$ – capillary diameter; $D_{\text{rup}}$ – horn diameter; $L_{\text{cap}}$ – capillary length; $L_{\text{caphorn}}$ – length capillary with horn.

**Figure 4.** Circular (a) and three-dimensional (b) patterns of the decelerating sapphire and copper capillary at an operating frequency of 0.675 THz matching with the extractor.
The directivity and operating frequency band width are reduced by increasing the horn beam angle. The width of the main lobe of radiation and its angle, on the contrary, increase. An increase of the length of the horn and a decrease of the beam angle lead to increasing the directivity, but this is accompanied by a withdrawal of the selected resonant frequency of 0.675 THz. In this case, a minimum reflectance is equal to -33.52 dB, and the frequency corresponds to 0.677 THz i.e. only 0.3% of the offset from the considered frequency of 0.675 THz.

4. Conclusions
A model of the radiating Cherenkov capillary and horn antenna with the coating of sapphire and copper at a resonant frequency of 0.675 THz was designed. The group velocity is in the range of 0.4-0.5 c, the effective shunt impedance $R_{sh}/Q = 30-35 \text{kOhm/m}$. The calculated horn antenna directivity provides ~ 10 dB, the reflection coefficient of the capillary output is less than -25dB, the width of the operating frequency band ~ 5%.

The capillary without antenna has the radiation directivity of ~ 6 dB and the reflection coefficient from the capillary output is more than -12 dB and worse other parameters. Cherenkov capillaries with the integrated radiating antenna allows to achieve a wide range of operating parameters for different geometrical dimensions. It should be noted that these capillaries are difficult for production because of small sizes and high manufacturing tolerances requirements.

References
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