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# Dielectrics for output windows of medium power gyrotrons

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For achieving optimal characteristics of gyrotron it is necessary to choose a suitable material for output window. Balance of relatively low dielectric losses, slowly dependent on temperature, and relatively high thermal conductivity are required for good heat removal. Certainly, modern low loss CVD diamond windows meet these requirements, but their price is too expensive for wide application.

In this paper we present an analysis of properties of several dielectric materials: boron nitride (BN), which is currently widely used for gyrotron output windows production, crystal Quartz, and Spinel.

Basing on experimentally measured dielectric losses of these materials and on their thermal properties we made a calculation of maximal achievable output power that can be transmitted through disks made of such materials.

## Boron nitride

Most of currently produced medium power (~10−100 kW) gyrotrons have output windows made of hexagonal pyrolytic BN. Its dielectric properties in sub-THz range were studied in our previous works [1,2]. Usual samples of BN have $\tan\delta \approx 10^{-3}$ at 140 GHz which is higher in comparison with other investigated materials. But the loss tangent temperature dependence is rather weak: it increases by only about 40% with temperature increasing from 25 to 700°C.

Another important characteristic is thermal conductivity of BN. Usual value used as estimate in practice is 45 W/m·K for the direction parallel the layers. However, according to the available publications [3,4], thermal conductivity of BN can reach at least 220 W/m·K for samples with high crystal perfection.

## Spinel

Spinel ($MgAl_2O_4$) is ceramic material with relatively low dielectric loss which is resistant to high temperatures. In our work we studied spinel samples obtained by microwave heating of ultrafine powder components [5].

Measurements of dielectric parameters (n and tanδ) were made using high-Q resonator technique (see [1] and Refs. therein) in the frequency range 50–300 GHz at temperatures 20–200°C. Unlike BN, spinel demonstrates rather strong temperature dependence of dielectric loss. It is illustrated in Fig. 1. At temperature of about 400°C dielectric losses in spinel become higher than that in BN.

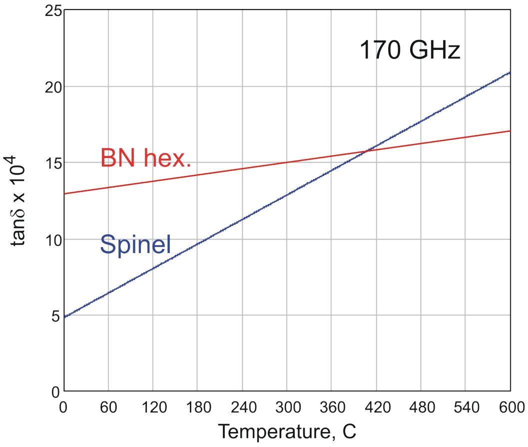

**Fig. 1.** Linear approximations of tanδ temperature dependencies at f = 170 GHz based on experimental data for spinel and hexagonal BN.

Thermal properties of spinel were taken from [6]. In comparison with BN it has several times lower thermal conductivity (18 W/m·K at room temperature).

## Quartz

Crystal quartz produced by Quartz Technologies Ltd was grown by the method of hydrothermal synthesis on the own raw material base of the deposit "Zhelannoe". The total concentration of impurities including alkali, gas-liquid and mineral elements does not exceed 2-3 ppm (chemical composition studies were carried out at the G.G. Devyatykh Institute of High-Purity Chemistry, ANZAPLAN analytical laboratories and QSIL laboratories). It has extremely low absorption coefficient in the optical range ($\leq 10^{-6}$cm$^{-1}$ at $\lambda = 1 \mu$m).

Investigation of quartz sample dielectric properties was made in frequency range 65–200 GHz at room temperature. Due to specific geometric sizes of the sample only $n_o$ component and corresponding value of tanδ were measured. Fig. 2 demonstrates experimentally measured frequency dependence of dielectric losses in quartz along the main axis. The losses in this sample are practically the lowest ones in comparison with earlier measured samples [1].

Thermal conductivity in quartz was taken from paper [7]: 6 W/m·K for [010] direction and 13 W/m·K for [001] direction at room temperature.

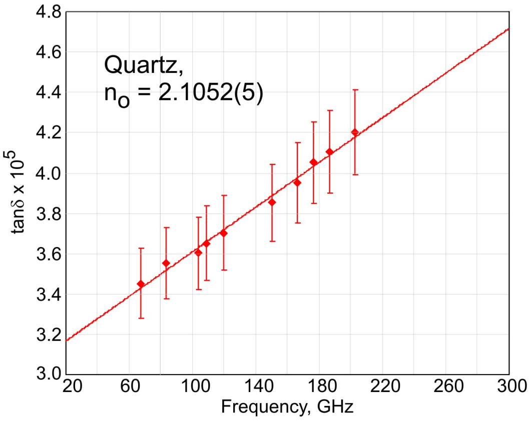

**Fig. 2** Experimentally measured frequency dependence of dielectric losses in quartz for the direction parallel to the main crystal axis. Line is the linear regression.

## Thermal calculation and discussion

Using data on dielectric losses and thermal properties of the samples we made a calculation of temperature distribution for a disks used as gyrotron output windows in the continuous-wave operation (CW). The calculation was made in a similar way as in [8]. We used Newton's law of cooling as the boundary condition on the perimeter. The coolant temperature was 30°C, and the coefficient of heat removal from the window perimeter was 4 W/cm$^2$·K. Heat flows from the window-vacuum and window-air boundaries were neglected.

The maximal output power for gyrotron windows made of BN and spinel was found as maximal beam power for which the temperature of the disk did not exceed 600°C. The thermal conductivity of BN was taken as 45 W/m·K. For quartz window the calculation is more estimative because we do not have information about the temperature dependence of tanδ. Besides, it is unlikely that quartz disk will withstand a large temperature gradient arising when the temperature of the disk center rises to 600°C. Thus, in our estimation of maximal power we limited maximal temperature of quartz to 300°C. For more strict calculation additional factors should be taken into account.

The window thickness was resonant, i.e., the optical thickness was equal to an integer number of half-wavelengths. The number of the half-wavelengths was chosen for the reason of the window strength. For disks with diameters of about 100 mm, the thicknesses ranged from 3 to 4 mm, and for disks with diameters of 30 mm (for f ~ 30 GHz), the thicknesses was 2-2.5 mm. Fig. 3 shows the maximal power transmitted through the window.

On the basis of Fig. 3 we can conclude that $MgAl_2O_4$ spinel is not optimal material for gyrotron output windows. Crystal quartz is a more suitable one, comparable to boron nitride in terms of maximum power level and even surpassing it at high frequencies. However, some problems associated with the use of crystal quartz may occur due to difficulty of soldering and possible mechanical stresses. Additional data on temperature dependence of tanδ are required.

Comparison of Fig. 3 (above) and Fig. 5 from [8] leads us to the conclusion that 6H-SiC disk can transmit several times more powerful beam than BN or quartz disks. But if we use BN with high crystal perfection and high thermal conductivity then such material can also provide several hundred kilowatts level for the CW mode in the sub-THz range.

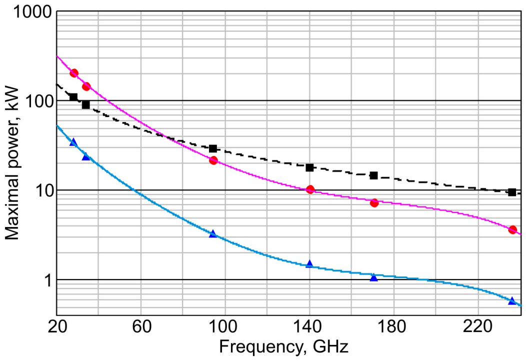

**Fig. 3** Maximal output power for hexagonal BN (circles), spinel (triangles) and quartz (squares). Curves are smooth approximations. See text for details.

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