Development of material processing system by using a 300 GHz CW gyrotron

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Abstract. High power THz-frequency material processing has great potential for the applications. The gyrotron is a microwave tube capable of delivering very high microwave power in the pulse and CW operation at the THz frequencies. The frequency of gyrotron is proportional to the intensity of magnetic field, because the operation results from the mechanism of “cyclotron resonance maser”. Therefore, in order to achieve high frequency operation, we need a high magnetic field which superconducting magnets or pulsed-magnets produce. We developed the material heating system by using a 300 GHz gyrotron. This system consists of a 300 GHz, 3.5 kW, CW gyrotron (Gyrotron FU CW I) with a cryogen-free 12 T superconducting magnet, a corrugated circular waveguide and an applicator.

1. Introduction
Remarkable progress in the microwave sintering of ceramics has been made since the 1980s, following the pioneering work by W. H. Sutton, M. A. Janny and H.D.Kimrey[1, 2]. Since then microwave sintering technology has been widely recognized to offer a number of advantages over conventional sintering process. Recently, the millimetre-wave (mm-wave) is promising as a new electromagnetic energy source for synthesis of new functional materials and surface modification[3]. Compared with the centimetre-wave of 2.45 GHz, the use of the mm-wave as an energy source shows several advantages such as homogeneous heating, steady heating due to the suppression of thermal run-away and small-sizing of the applicator. Further, the effect due to high frequency (mm-wave) and strong electric field is manifested in the mass transfer densification in the sintering of ceramic[4]. Achieving the submillimeter-wave material processing is expected from a technological and scientific point of view.

Gyrotrons are oscillator tubes based on the Electron Cyclotron Maser instability. The free energy is the rotational energy of a relativistic electron beam in a longitudinal magnetic field. A coherent transfer of the energy from the gyrating electrons to the electromagnetic wave in the interaction circuit occurs due to the azimuthal phase bunching when the wave frequency is somewhat larger than the relativistic electron cyclotron frequency or one of its harmonics. Gyrotrons have many advantages. The resonant circuit is very simple, so we are able to have a high permitted heat loss. The permitted total injection electron beam energy is very high for the simple structure of the electron gun. The phase bunching for cyclotron motion of electrons results in the oscillation of gyrotron, so the length of the interaction region is not restricted by oscillation frequency. These advantages enable high power and high efficiency operation even at
the millimeter and submillimeter wave regions. Internationally, the development of gyrotrons is proceeding in two directions. One is the development of high power, millimeter wavelength gyrotrons as power sources for electron cyclotron heating of the fusion plasma. The other is the development of high frequency, medium power gyrotrons as the millimeter to submillimeter wavelength sources for measurements. The gyrotrons developed at the University of Fukui (the so-called "Gyrotron FU series") belong to latter group. Medium power, high harmonic gyrotrons in the University of Fukui have achieved frequency tunability in the wide range of 38 GHz to 889 GHz along with high powers in the range of several tens watts to several tens kilowatts[5]. Such sources have many advantages for applications to various fields including the far-infrared spectroscopy, the measurement of material properties[6, 7], polarization-enhanced NMR spectroscopy[8], plasma diagnostics[9, 10] and material precessing[11, 12].

2. Submillimeter-wave material processing system
Figure 1 shows the schematic drawing of the submillimeter-wave material processing system. Each component is explained in the following sections.

2.1. Gyrotron FU CW I
Gyrotron FU CW I have been developed in conjunction with the Institute of Applied Physics (IAP), Russia. A 12 T cryogen-free superconducting magnet (CFSCM) is used for a generation of a main magnetic field (as shown in figure.2). The frequency of a gyrotron is always very close to the cyclotron frequency of the electrons

\[ f(\text{GHz}) = 28 \frac{B(\text{T})}{\gamma} \]  \hspace{1cm} (1)

or to its harmonics. Here \( B \) is the magnetic field and \( \gamma \) is the relativistic factor related in the following way to the electron beam energy \( eU \):

\[ \gamma = 1 + \frac{eU}{511(\text{keV})}. \]  \hspace{1cm} (2)
Table 1. Operating parameter design of Gyrotron FU CW I.

| Parameter                              | Value                  |
|----------------------------------------|------------------------|
| Frequency                              | 300 ± 2 GHz            |
| Maximal CW output power                | 3.5 kW                 |
| Range of CW output power               | 0.5-3.5 kW             |
| Cavity radius                          | 8.39 mm                |
| Cavity Q factor                        | 6000                   |
| Operating cavity mode                  | TE_{22,8,1}            |
| Type of gun                            | quasi-diode            |
| Maximal beam voltage                   | 16 kV                  |
| Maximal beam current                   | 1 A                    |

Figure 3. Photo of an applicator which was designed for 300 GHz material processing.

The 300 GHz operation of a gyrotron in the fundamental operation condition requires the magnetic field of 10.9 T. As shown in table 1, the gyrotron has a quasi-diode electron gun and operates on the TE_{22,8,1} cavity mode. The output power of the gyrotron is smoothly varied in the range of 0.5 kW to 3.5 kW by a change of electron beam voltage. The output window waveguide has a diameter of 80 mm. To optimize performance in gyrotron operation, additional small solenoids are settled under the CFSCM. The electron beam current is automatically stabilized at a pre-set value by a specialized power supply having a feedback loop.

2.2. Applicator

The applicator was designed with cylindrical sample processing space φ 450 in diameter and 880 mm in length as shown in figure 3. Both volumetric heating by uniformly distributed microwave energy and surface heating by a high intensity focused wave beam can be performed in this applicator. To perform surface heating of samples, the focusing mirror is installed as shown in figure 4. The electromagnetic wave power is concentrated in the spot with the size of about \((2λ)^2\). On the other hand, to perform uniform volumetric heating of materials, the homogeneous electromagnetic field distribution is produced by a corrugated sheet and a mode stirrer, which is
mounted on the back wall as shown in figure 3. The applicator has six ports for a measurement, two vacuum ports and a peephole with punch board and tempered glass. The applicator is cooled by using the water jacket.

2.3. Corrugated waveguide
The submillimeter wave beam from gyrotron has to be transmitted to applicator by low-loss transmission line. To achieve the low-loss transmission at the frequency of 300 GHz, the over coupled corrugated waveguide (ID = 6.35 cm) has a fine structure with corrugated period and depth of 254 μm[13]. figure 5 shows the cut view of a manufactured corrugated waveguide. To manufacture such fine structure by machining, brass was chosen rather than copper or aluminium. However, the ohmic loss is not negligible in the system performance. To reduce the ohmic loss, the surface of the waveguide was plated by Ni and Au. Each piece is able to join each other.

3. Conclusion
We developed the material processing system by using a 300 GHz gyrotron as an radiation source. This system consists of a 300 GHz, 3.5 kW, CW gyrotron with a cryogen free 12 T superconducting magnet, a corrugated circular waveguide and an applicator. The circular corrugated waveguide (ID = 6.35 cm) with a corrugated period and depth of 254 μm have been designed. The applicator have been designed both volumetric heating by uniformly distributed microwave and surface heating by a focused wave beam. At the present time, a study of the non-thermal effect on ceramics sintering, which depends on the frequency of electromagnetic energy source, is progressing by using this submillimeter material processing system.

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