18PB-004

Development of Millimeter Band BWO with Interdigital Slow Wave Structure on Quartz Wafer

石英基板上に形成したインタデジタル遅波回路を有するミリ波帯BWOの開発

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An interdigital slow wave structure (SWS) for millimeter band backward-wave osicillator (BWO) has been developed. The simulation of BWO radiation is performed by a particle-in cell (PIC) method in which an interaction between confined flow of electron beam and electro-magnetic waves is considered. In PIC simulation, we observed the radiation at frequency around 40 GHz when the electron beam is modulated by an intended mode. The radiation mode obtained by the PIC simulation shows good agreement with a simple prediction from the dispersion curve of the SWS. The fabrication of the interdigital aluminum pattern on a quartz wafer as a SWS was achieved by a semiconductor manufacturing process.

1. Introduction

Terahertz radiation, which is located between electronics and photonics, is expected to have various applications. Therefore, there has been considerable interest in THz sources, such as solid state oscillators, lasers and vacuum electronic devices [1].

We focused on BWOs which radiate a tunable continuous wave with a tabletop size. Because of these features, BWOs have been expected to use for the materials spectroscopy, THz imaging [2] and high-date-rate communications. In this paper, we designed an interdigital SWS for 40 GHz band by electro-magnetic analyses. In addition, we verify the propriety of the designed SWS by comparing with the result of a radiation simulation by a PIC method.

2. Interdigital SWS

In order to grow an oscillation in a BWO, the phase velocity of the microwave must be close to the velocity of an electron beam. On a SWS the phase velocity of microwave can be matched to the electron's velocity. An interdigital SWS is constructed by two metal combs on a substrate shown in Fig.1. Microwave meanders through the circuit.

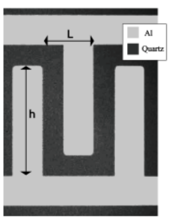

Fig.1 Interdigital circuit on wafer.

We estimate that the phase velocity in the SWS by considering the interdigital structure to be a coplanar strip line [2]. In this analogy a phase difference per period of the structure may be written as

$$\phi = (\mathrm{L}+\mathrm{h}) \times \frac{2\pi}{\lambda} + \pi$$
$$= (\mathrm{L}+\mathrm{h}) \times \frac{2\pi f}{v_g} + \pi$$

In this equation we assumed that a microwave

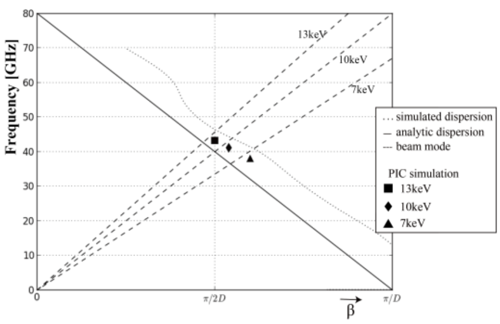

Fig.2 Dispersions of interdigital SWS and beam modes at energy of 7, 10, 13 keV. PIC simulation results are indicated by symbols. The horizontal represents propagation constant $\beta = \phi/L$.

propagates along the two combs. The dispersion curves are shown in Fig.2. These curves support the fact that in the interdigital SWS a fundamental wave is backward. The oscillation is expected on a frequency at the intersection of the dispersion and beam mode. The dimensions of L and h are determined by the prediction that dispersion curve intersects with 10 keV beam mode at the position of $\beta = \pi/2L$, f =40 GHz. i.e. it is designed to match $\pi/2$ mode.

The dotted curve is obtained by the result of electro-magnetic simulations. The dispersion diagram indicates that $\pi/2$ mode of the wave is excited by beam with energy of 13 keV at the frequency of 46 GHz.

3. Simulation

The radiation simulation of the designed SWS is performed by the particle in cell (PIC) method. The DC electron beam with cylindrical shape of radius 1mm is emitted close to the SWS along the substrate parallel with energy of 7-13 keV, current of 12 A/cm^2 under an axial magnetic field applied by a cylindrical permanent magnet.

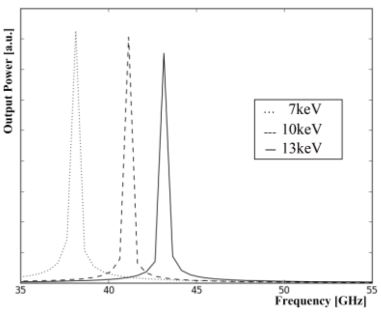

Fig.3 FFT analyses of the port signal.

FFT analyses of port signals obtained by the simulation shows that the radiation has a strong peak at a frequency of 41 GHz stimulated by the 10 keV beam as shown in Fig.3. The result is in good agreement with the prediction by the dispersion of the SWS in Fig.2. It is found that the radiation frequency can be controlled by the energy of electron beam. This is the reason why BWOs are called tunable devices.

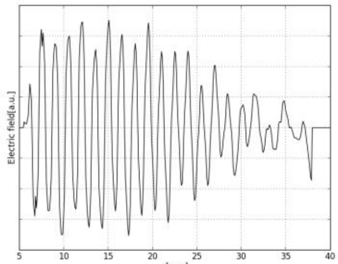

Fig. 4 Electric field distribution in the axial direction. Electron beam flows from left to right.

Figure 4 represents a spatial distribution of the electric field of radiation at frequency of 40GHz in a steady state of the oscillation. The gradual growth of the electric field towards the upper region indicates that the radiation behaves as a backward wave. A phase per period of the SWS and a propagation constant β of the wave can be estimated by the electric field distribution. The β are plotted in Fig. 2. We can see that $\pi/2$ mode is excited by 13 keV beam. The good agreement between the result of the PIC simulation and the prediction of the dispersion suggests that an estimation by electro-magnetic simulation without beam described in the previous section is useful for design of SWS.

4. Fabrication of SWS on wafer

We fabricated an interdigital pattern on a quartz wafer by sputtering of aluminum. Figure 1 shows a microscope image of a SWS.

The maximum thickness of deposited Al is 100 nm since in our method the thickness is limited by the scale in the minimal structure of 0.185 mm. On the other hand, a skin depth of Al at 40 GHz is estimated at 400 nm. Therefore it may be required to develop the method for more thick deposition of metal.

5. Summary

We designed an interdigital SWS for a BWO at 40 GHz band. The SWS was fabricated by sputtering. The electro-magnetic analyses show that dispersion of microwave intersects with 13 keV beam mode as the $\pi/2$ mode. The radiation signal at port was observed in the PIC simulation. The radiation mode obtained by the PIC simulation shows good agreement with a simple prediction from the dispersion curve of the SWS.

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