§19. Bloch Wave Cavity in Millimeter and Sub-Millimeter Wave Regions

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This project is aimed at studying Bloch wave cavity formed on rectangularly corrugated cylindrical waveguides. The corrugation has amplitude h, width d and period z_0. The corrugation wave number is given by $k_0 = 2\pi/z_0$. From the point of view of electromagnetic materials, the corrugated wall is a surface with sub-wavelength structures. Pendry *et al*. pointed out that such structured surfaces form surface plasmon polariton-like (SPP-like) bound states and hybrid surface plasmons[1]. And the highly confined guiding of the SPP-like waves has been verified using a planar plasmonic metamaterial.[2] The SPP-like waves on a periodically structured surface are called Bloch waves in this study. In a cylindrical geometry, the boundary condition on the side ends of a planar corrugation is replaced by an azimuthally periodic condition in the cylindrical coordinate system and axisymmetric and non-axisymmetric cylindrical Bloch waves are formed. Note that the corrugations are structured on the inner wall of waveguide (the concave cylindrical surface) or the outer wall of cylinder (the convex cylindrical surface). And the Bloch waves can exist on the both corrugated surfaces.[3]

Since the Bloch waves are clinging to the cylinder and are reflected at the corrugation ends, they form a Bloch wave cavity like a conventional cavity resonator. Electromagnetic properties of cavity mode can be examined based on a cavity resonance technique, in which the microwave reflections and/or transmissions are measured as a function of frequency using a network analyzer. We apply this technique to examine a K-band Bloch cavity on the convex cylindrical surface in the microwave region.[4] Resonance curves obtained directly verify the Bloch wave cavity and show that the Bloch waves are classified into two types. One is “bounded surface wave” around the upper cut off at the π point ($k_z z_0 = \pi$), in other words, border of the first Brillouin zone. The other is “hybrid surface wave” in the region away from the upper cut off. The latter has similar properties as the Sommerfeld wave on a smooth metal wire.

The Bloch wave cavity can be excited by an electron beam. Some of excited Bloch waves may be reflected at the ends of the cavity and the other is converted to radiating waves which is used to examine the Bloch wave cavity. We use a G-band corrugation on the concave surface of cylindrical waveguide to form the Bloch wave cavity.[5] The corrugation parameters are measured using elongated images obtained by a digital microscope. Fig. 1 shows dispersion curves of the fundamental axisymmetric transverse magnetic (TM_{01}) mode with the parameters in Table I. This is a Bloch wave with a phase velocity slower than the velocity of light. It becomes a bounded surface wave near the upper cutoff frequency. And terahertz BWO operations are realized with the relatively low beam energy less than 100 keV as shown in Fig. 1. The axial boundary conditions caused by the reflection at both cavity ends should be considered. Two thresholds originated from the current and the energy are imposed to excite intense Bloch waves in the cavity. And the latter is more critical for terahertz intense BWO operations. The radiation patterns are broad and may not be explained by a single mode operation of the TM_{01}-Bloch wave. Non-axisymmetric as well as axisymmetric Bloch waves can exist very close to each other. They may be excited by the electron beam and the G-band Bloch wave cavity is a multimode system.

Table 1 Parameters of rectangular corrugations

	h [mm]	z_0 [mm]	d [mm]
Design	0.15	0.5	0.3
Fabricated	0.175	0.50	0.29

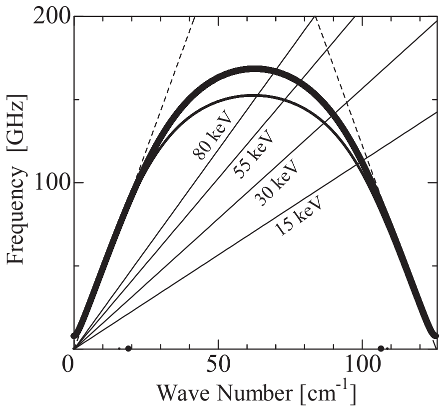

Fig. 1. Dispersion curves of TM_{01}-Bloch wave for G-band corrugated hollow waveguide. Thick and thin solid curves represent the designed and fabricated corrugations, respectively. Dotted lines are light lines. The beam lines for 15 keV, 30 keV, 55keV, and 80 keV are also plotted.

The Bloch wave cavity is directly verified by a BWO operation driven by an electron beam as well as the cold test technique using a network analyzer. It may be useful to study electromagnetic properties of the periodic corrugation and also of considerable interest for practical use and development of terahertz wave technique.

1) J.B. Pendry et. al. : Science 305 (2004) 847.
2) C. R. Willams et. al.: Nature Photonics 2 (2008) 175.
3) K. Ogura et. al. :IEEE Trans. Plasma Sci. 41 (2013) 2729.
4) K. Yamazaki et. al.: *Plasama Conference 2014* (Nov. 2014, Niigata, Japan) 18PB-024.
5) S. Gong et. al. :*5th Euro-Asian Pulsed Power Conference* (Sept. 2014, Kumamoto, Japan) P1-66.