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Analytical Design of SWS for a THz BWO for Spectroscopy and Medical Imaging

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Abstract

Compact, coherent, high power, THz sources of frequency varying from 0.1THz to 5THz are required for their applications in near-field Microscopy, Spectroscopy, Imaging, Radar, etc. There are need for both CW and pulsed compact high power THz sources of wide tuning range. Different types of THz sources based on optical device, solid state device and vacuum electronic device (VED) are compared. VED is selected for further investigation because of its high power, high efficiency and low cost. Among VEDs, backward wave oscillator (BWO) is the most preferred THz source because of its compact size, simplicity and wide tuning range. Simplified analytical approach is presented for determining design parameters of slow-wave-structure (SWS) for a THz BWO. Staggered double-vane loaded rectangular waveguide SWS (SDV-SWS) type planar RF structure is selected for a THz BWO because it is easier to fabricate by MEMS technology with high precision and surface finish and it is inherently compatible for sheet beam operation. Design parameters of SDV-SWS for a 0.22THz BWO and a 1.2THz BWO are presented.

Keywords: THz sources, THz BWO, THz Microscopy, THz Spectroscopy, THz Medical Imaging, THz Radar

1. Introduction

THz frequencies from 0.1THz to 10THz are part of the electromagnetic spectrum falling between the microwave and the infrared regions as shown in Fig.1. Over the last 2 decades, THz frequencies also called T-rays are being investigated extensively in many applications related to near-field microscopy, spectroscopy, imaging, security, ultra high data rate communication, high resolution radar, etc. [1-4]. This is because T-rays have many distinctive characteristics. THz waves penetrate easily through clothing, skin and many synthetic and organic materials, and get strongly absorbed by water molecules. Many materials including bio molecules and chemicals have their molecular resonance frequencies within THz range (0.2-5THz). Also, the energy quanta of THz frequencies are much less (tens of milli eV) compared to that of X-rays. Therefore T-rays cause no ionization hazard to the biological tissues.

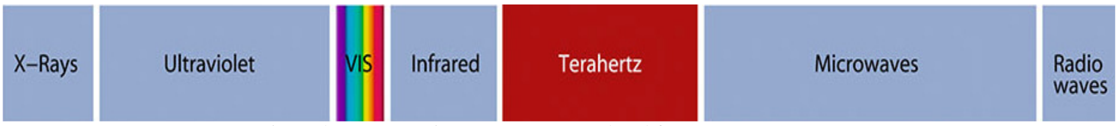

Fig.1 Electromagnetic Spectrum – (THz band from 0.1THz to 10THz)

THz near field microscopy provides images at nano scale resolution with detailed spectroscopic information of biological cells, chemicals and other materials. THz spectra of such bio molecules and materials are distinct to analyze small changes of the molecular structure. Therefore, THz technology is used to investigate conformational molecular changes in bio molecules like myoglobin and hemoglobin. THz imaging is being explored in medical diagnosis like early detection of skin, breast and colon cancer, osteoarthritis, tooth decay, blood test, etc. THz system is also helpful during surgical operation as it provides safe and high resolution imaging.

2. THz Sources

The most critical component for a successful THz system is the requirement of a suitable source for generation of THz frequencies. There is a need to achieve compact, coherent, economical and efficient broadband THz source for generating higher and higher output power (more than 100mW) over the frequency band of 0.2-5THz of spectroscopic interest. Both CW (continuous wave) and pulsed high power THz sources of wide tuning range are required. For this purpose, two different approaches have been pursued for generation of THz frequencies: downward from optics (by mixing of two optical signals) and upward from electronics (solid state and vacuum electronic devices). Various THz sources are grouped into three broad categories:

i. Laser and photonic devices (quantum cascade laser, optically pumped molecular laser, etc.),

ii. Solid state electronic devices (Gunn oscillator, Schottky diode multiplier, etc.),

iii. Vacuum electronic devices (TWT, BWO, Klystron, Magnetron, Gyrotron, FEL, etc.).

The laser based optical devices like quantum cascade lasers (QCLs) can generate hundreds of mW output power in high frequency range from 2THz to 20THz. There are both CW and pulsed QCLs that are being used in various THz experiments. But these devices are limited to frequencies more than 2THz. Also, these devices are very expensive and bulky to develop, and are not economical for commercial use. On the other hand, both vacuum electronic devices and solid-state devices can generate maximum frequency up to 2THz. Solid-state devices are able to generate power only tens of μW at 1THz. GaN based solid state devices are being developed to generate mW level power up to 2THz. Vacuum electronic devices (VEDs) are able to generate tens of mW output power at frequencies up to 2THz, and are more efficient. Among various types of VEDs, backward-wave oscillator (BWO) is the most preferred THz source because it has relatively low operating voltage and is simple, compact and tunable easily over wide range.

3. Backward-Wave Oscillator (BWO)

The operation of a BWO, as shown in Fig.2(a), is based on the interaction of a high-energy electron beam with the electromagnetic field travelling inside an RF slow-wave structure (SWS). The phase velocity of the e.m. wave is slowed to nearly synchronous with the electron beam velocity which results in formation of beam bunching and net energy transfer from the electron beam to the RF circuit field. In the BWO, the RF energy travels in the direction opposite to the flow of electron beam due to negative group velocity. The RF field builds up from output to input whereas the electron beam bunching builds up from input to output. Therefore efficiency of a BWO is relatively less compared to a travelling-wave-tube (TWT) but it is tunable easily over wide band. BWO can generate hundred watts of power at 0.1THz to tens of mW power at 2 THz.

In another arrangement, TWT with feedback from the output to the input is used for RF power generation, as shown in Fig. 2(b). TWT is a forward wave amplifier where both the phase velocity and the group velocity of the e.m. wave are in the direction of the electron beam. The RF field grows from the input to the output as the electron beam bunching and therefore it has higher interaction efficiency compared to a BWO as shown in Fig. 2(a). Also, TWT with feedback provides more stable coherent source but it is not easily tunable over wide band as BWO.

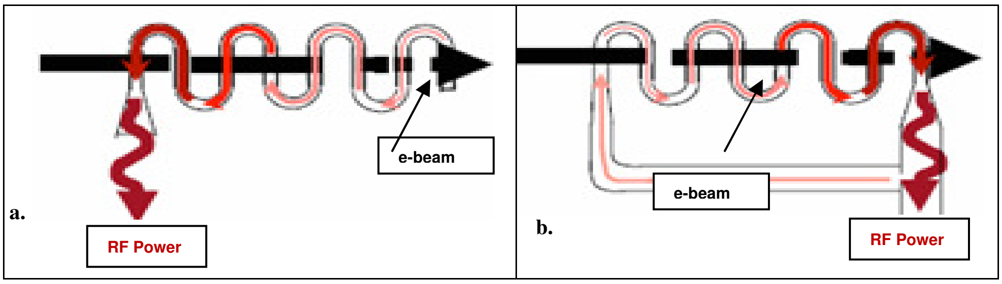

Fig.2 Compact vacuum electronic source: (a). Conventional backward wave oscillator, (b). Regenerative TWT oscillator

Planar RF structure are preferred for a THz TWT / BWO because planar structure due to its small dimensions is easier to fabricate by micro-fabrication technology like UV-LIGA, DRIE or nano CNC machining with high precision and surface finish. Also sheet electron beam is preferred over the conventional cylindrical beam as it has higher beam current capacity due to drastically reduced space charge field. Therefore, the output power can be increased with a sheet beam over a cylindrical beam as sheet beam provides higher current carrying capacity, larger interaction area with lower current density, and smaller focusing magnetic field. Major components of a compact planar THz TWT / BWO are:

(i) Electron gun with thermionic cathode for generating an electron sheet beam of suitable shape and size at required beam voltage and beam current;

(ii) Slow-wave circuit of wide bandwidth, high impedance and low circuit loss for supporting THz waves;

(iii) Input and Output couplers with minimum reflection and insertion loss;

(iv) Periodic permanent magnetic focusing for confined flow of the sheet beam through the structure with minimum beam interception; and

(v) Collector for recovering maximum energy from the spent electron beam with zero back streaming.

3.1 Analytical Approach of Determining SWS parameters for a THz BWO

Staggered double vane loaded rectangular waveguide slow wave structure (SDV-SWS), as shown in Fig.3, is selected for a THz BWO because it has higher interaction impedance, wider bandwidth and low circuit loss compared to other structures. Also, this is a planar structure that is easier to fabricate by conventional MEMS technology and is inherently compatible with the operation of sheet electron beam.

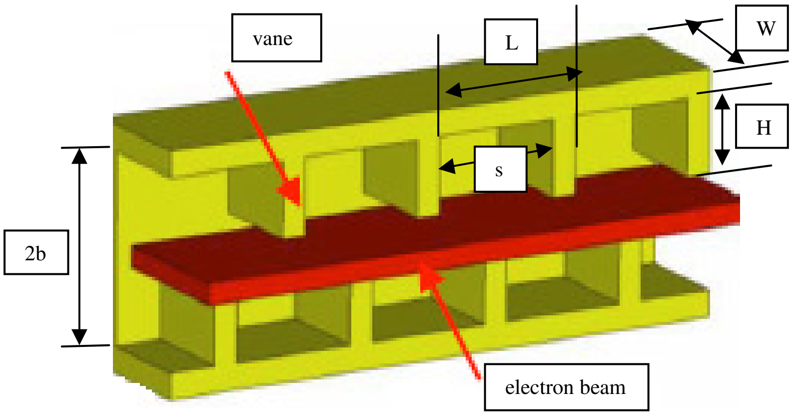

Figure 3: Staggered double-vane Slow-Wave Structure with sheet electron beam; design parameters are marked.

The dispersion plot of SDV-SWS with beam velocity lines is shown in Fig.4. SDV-SWS is a forward fundamental structure, and the beam velocity line is chosen to intersect with the first backward space harmonic (n = -1) for BWO operation. The circuit bandwidth for the backward wave space harmonic is $f_U - f_L$ where f_U is the upper cut-off frequency and f_L is the lower cut-off frequency. The beam velocity decides the oscillation frequency. As shown in the figure, the oscillation frequency is around 0.213THz with 30kV beam and it is tunable over 0.186THz (20kV) to 0.227THz (40kV). Simplified analytical approach is developed for determining the dimensions of unit cell of SDV-SWS for a THz BWO. The approach is analogous to the analytical approach [5] as developed for TWT operating for n=+1 forward space harmonic.

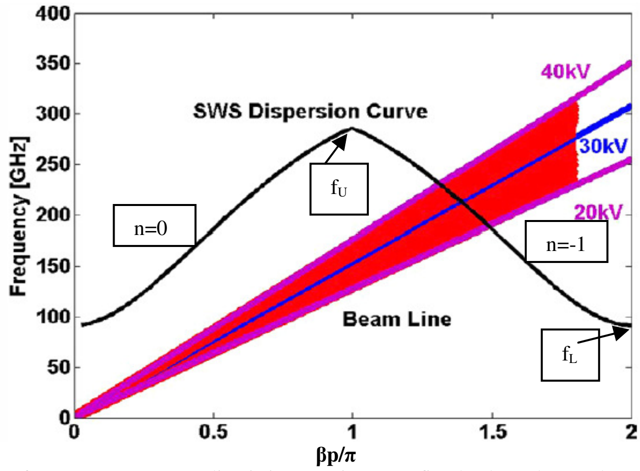

Figure 4: Dispersion Curve for SDV-SWS. Beam line is intersecting n=-1 first backward space harmonic for BWO operation.

The width (W) and height (2b) of the rectangular waveguide are first decided as per the frequency band. The lower cut-off frequency (f_L) of the dispersion curve corresponds to the cut-off frequency of the dominant TE_{10} mode of the rectangular waveguide as eq. (1):

$$f_L = c / 2W \quad (1)$$

Where, c is the velocity of light. The upper cut-off frequency f_U corresponds to the cut-off frequency of higher mode TE_{11} of the rectangular waveguide of width (W) and height (H), as eq. (2):

$$f_U = \frac{c}{2}\sqrt{W^{-2} + H^{-2}} \quad (2)$$

Other dimensions such as pitch (L), vane height (H), gap length (s) are optimised to achieve desired dispersion and impedance characteristics using the following set of equations.

The relativistic electron beam velocity (u_0) is determined by the beam voltage V_0,

$$u_0 = c\sqrt{1 - \frac{1}{(1 + V_0/511\,)^2}} \quad (3)$$

where, V_0 is in kV, and c is the speed of light.

At design centre frequency (f_c), phase velocity (v_p) of the RF wave is considered (~90%) of the electron beam velocity (u_0):

$$v_p = 0.90u_0 \quad (4)$$

This phase velocity v_p corresponds to the phase shift per pitch (βL) equals to (π+0.5π) for n=-1 space harmonic at design centre frequency (f_c).

$$\beta L = 1.5\,\pi \quad (5)$$

$$\beta = \omega / v_p \quad (6)$$

where, β is the axial propagation constant (radian/m) and ω is the angular frequency ($2\pi f_c$). Pitch (L) of the vanes is determined from eqs (3) to (6).

The vane height (H) is decided by the need of the suitable beam tunnel height (2a). The beam tunnel height (2a) is determined by the condition of high interaction impedance of the circuit using eq. (7):

$$\beta a = 1.0 \quad (7)$$

Therefore, the vane height (H) is determined by (b-a). Ideally, vane height (H) should be as large as possible for high impedance of the structure but it is to be compromised as eqs. (2) and (7). The vanes on the opposite sides in the waveguide structure are staggered by half a period (d=L/2) for wide bandwidth and high impedance of the structure, as it provides proper axial component of the RF electric field for efficient interaction with the electron beam. The vane shape can be rectangular, trapezoidal, conical or cosine in shape. Each shape has its merits and demerits in terms of bandwidth, impedance and loss. Rectangular vane is chosen for simplicity in fabrication and high impedance.

The gap (s) between two adjacent vanes on the same side of the waveguide should be chosen as large as possible to achieve high axial electric field (E_z) component in the interaction gaps. Gap length (s) is selected up to 75% of a pitch, compromising vane thickness:

$$s = 0.75\ H \quad (8)$$

The large value of (s) although has higher impedance but it may cause too thin vanes which may be difficult to fabricate and handle, and therefore it needs to compromise with the suitable vane thickness.

The above approach is validated by comparing the determined designed parameters of two tubes with the published design parameters that were optimized using 3D e.m. field simulators.

3.2 Design parameters of SWS for a 0.22 THz BWO with single sheet beam

For a BWO of centre frequency (f_C) 0.2134THz and output power 100W, the electron beam of beam voltage 30kV is selected as per the given published paper [6]. The lower cut-off frequency f_L is given around 0.125THz, and the upper cut-off frequency f_U is given 0.325THz. The parameters of unit cell of double-vane SWS are analytically determined using eqs. (1) to (8), and are summarized in Table-1. The analytically calculated design values are found in reasonably good agreement with the published designed data [6]

TABLE 1: PARAMETERS OF RF STRUCTURE FOR 0.22THZ BWO (30KV BEAM VOLTAGE, CENTRE FREQ. 0.2134THZ)

PARAMETER	ANALYTICAL (µM)
PITCH [L]	320
GAP[S]	240
BEAM TUNNEL [2A]	150
VANE HEIGHT [H]	175
W/G HEIGHT [2B]	500
W/G WIDTH [W]	1200

3.3 Design parameters of SWS for a THz BWO with Two sheet beams

It is challenging to develop high power BWO of frequency more than 1THz as dimension of the structure will become further small (at least by 5 times smaller of the above designed 0.20THz BWO). The beam current density also enormously increases for a high power BWO which is not easy to generate. To overcome this problem, the SWS as discussed in section 3.2 is modified for operating in higher order TM_{n1} mode with the n-number of sheet electron beams. BWO radiation is obtained from the interaction of multiple sheet electron beams with backward wave operating in the high-order mode.

The given analytical equations (1) to (8) can be used to determine all parameters for each part of the modified structure operating in high-order mode. Fig.5 shows ridge-loaded SDV-SWS with 2-sheet beams [7]. The ridge of width Wr and height Hr on the upper and the lower half vane-loaded sections divide the waveguide structure in two parts. The width (w_1) of each rectangular waveguide section decides the lower cut-off frequency. Width (w_1) is defined as:

$$w_1 = 0.5W - Wr \qquad (9)$$

The lower cut-off frequency (f_L) of the rectangular waveguide structure of width (W) 320µm and ridge of width (Wr) 60µm is calculated by eq.1, and it is 1.15THz.

The upper cut-off frequency f_U of the rectangular waveguide of width (w_1) and height (2b), is decided by eq. (2). The upper cut-off frequencies is 1.45THz for height (2b) 160µm. For 19.5kV beam voltage, other parameters are determined using the above sets of eqs. (3) to (8). The pitch of the vanes (L) is decided as 60µm and vane height (H) is decided as 60µm.

The parameters of the ridge-loaded SDV-SWS are given in Table-2. The analytically designed parameters of unit cell of double-vane SWS as summarized in Table-2 are compared with the published designed data for a 1.20THz BWO operating at 19.5kV beam voltage. The parameters as achieved using the above given analytical approach are found in good agreement with the data as given in [7]. The lower and the upper cut-off frequencies nearly 1.15 THz and 1.45THz are also close to the values as given in [7].

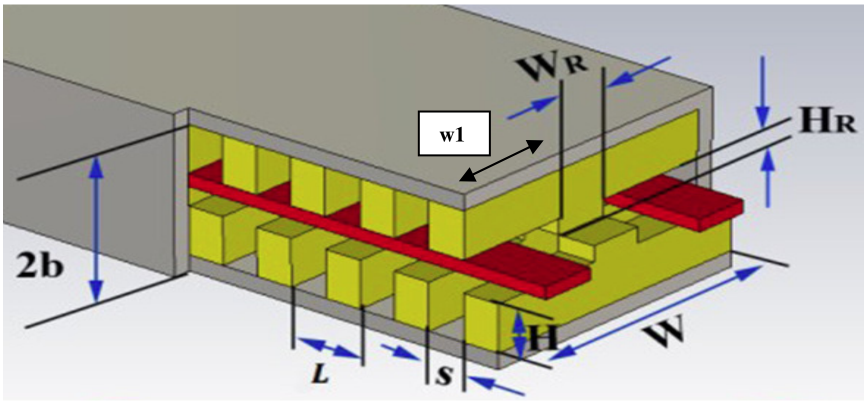

Figure 5: Ridge-loaded SDV-SWS with 2 sheet beams for 1.2THz BWO with 2 sheet beam, each of size 30μm (thick) x 100μm (width).

TABLE 2: PARAMETERS OF RF STRUCTURE FOR 1.2THZ BWO

PARAMETER	ANALYTICAL (μM)
WAVEGUIDE WIDTH W	320
WAVEGUIDE HEIGHT 2B	160
VANE (GRATING) HEIGHT H	60
SWS PERIOD L	60
GAP LENGTH S	30
RIDGE WIDTH WR	60
RIDGE HEIGHT HR	20
LOWER & UPPER FREQS.	1.15 THZ & 1.45 THZ

The above approach of using 2-beams interaction with higher mode TM_{21} in the ridge-loaded SDV-SWS structure can be further extended for BWO of increasing frequency and output power. Interaction of 5-beams with TM_{51} mode structure can be used for a much higher power and higher frequency THz BWO.

4. Conclusion

High power, compact and economical THz sources are needed for many emerging applications like spectroscopy, imaging, high resolution radar, and other areas ranging from biology and medicine to chemical, pharmaceutical and material sciences. Among different types of THz sources, BWO (vacuum based device) is investigated because it is a compact, high power source with easy wide band tuning. Also, BWO is preferred because of its simplicity and low cost for various applications. Simplified analytical approach is presented to determine design parameters of a staggered double-vane SWS for a high power THz BWO, operating with sheet beam. For 1.2THz, 1W BWO, a new design approach is presented which is based on the interaction of two electron beams with second higher order mode in the specially divided waveguide structure. The presented simplified analytical approach can also be used to determine the design parameters of SWS for a high power THz BWO, operating with more than two sheet beams.

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