Hybrid systems with virtual cathode for high power microwaves generation

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Abstract

It is shown that use of a photonic crystal enables to construct several types of hybrid systems with virtual cathode, which could radiate due to different radiation mechanisms (bremsstrahlung and diffraction (transition) radiation) with different frequencies. Also mentioned that photonic crystal makes possible to create phase-locked array of generators.

Key words: virtual cathode, free electron laser, volume free electron laser, volume distributed feedback, diffraction grating,, diffraction radiation, photonic crystal, traveling wave tube, high power microwave

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Interest to high power microwave (HPM) sources has emerged in recent years due to revealing new applications and offering novel approaches to existing applications.

Vacuum electronic sources, which convert the kinetic energy from an electron

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beam into electromagnetic field energy, are a natural choice for generating HPM.

The high current density electron beam, once generated, propagates through an interaction region, which converts the beam's kinetic energy to HPM. It is the particular nature of the interaction that distinguishes the various classes of sources.

High power HPM sources generating high electromagnetic power density require the high power densities in the electron beams, where space-charge effects are essential.

When the magnitude of the current I_b of an electron beam injected into a drift tube exceeds the space-charge-limiting current I_{limit}, an oscillating virtual cathode (VC) is formed [1,2].

According to [1] the following formula gives a good approximation for the space-charge-limiting current:

$$I_{limit}(kA) = \frac{mc^3}{e} G(\gamma^{2/3} - 1)^{3/2} \tag{1}$$

where m and e are the mass and charge of an electron, c is the speed of light, γ is the Lorentz factor of the electron beam and G depends on the geometry [1,3]. For example, for an annular electron beam in a cylindrical drift tube G reads as follows [3]:

$$G = \frac{1}{(\frac{r_b - r_b^{in}}{r_b} + 2\ln\frac{R}{r_b})(1 - sech\frac{\mu_1 L}{2R})}, \tag{2}$$

where r_b and r_b^{in} are the outer and inner radius of the electron beam, R and L are the radius and length of the cylindrical drift tube and μ_1 is the first root

of the Bessel function $J_0(\mu) = 0$.

When oscillating virtual cathode is formed two types of electrons exist: those oscillating in the vircator potential well and passing through the vircator area (see Fig.1).
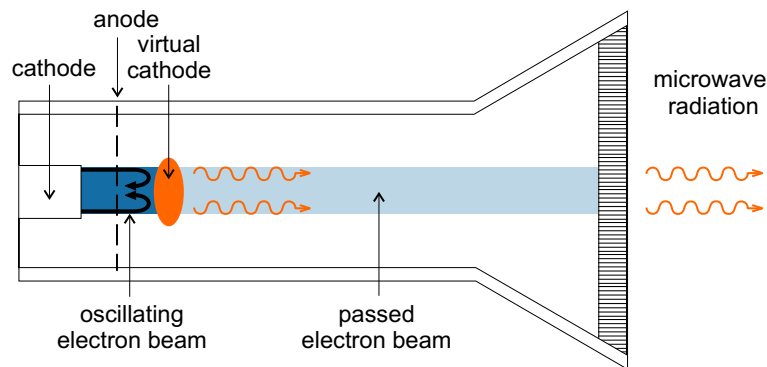

Fig. 1. An oscillator with virtual cathode

For electrons oscillating in the area "cathode-anode-virtual cathode" two radiation mechanisms provide radio-frequency signal [6]:

1. one radiation mechanism originates from the oscillations of the reflected electrons about the anode foil (electron oscillations in the potential well "cathode-anode-virtual cathode"). A microwave signal is generated at a frequency of roughly $\frac{c}{2d_d}$, where d_d is the anode-to-cathode spacing.

2. The other radiation mechanism is the oscillation of the virtual cathode at a frequency near the plasma frequency ω_p of the space charge density that is formed. That is

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m}} \tag{3}$$

where n_e is the number density of the electrons in the space charge configuration (in the plane of the anode grid) [6].

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The essence of the above radiation mechanisms is bremsstrahlung radiation ensuing from electron deceleration.

In the present paper we emphasize that bremsstrahlung radiation from electrons oscillating in an electron beam with a virtual cathode is accompanied by transition radiation, which origin is electron velocity rather then acceleration. Use of a photonic crystal enables to construct several types of hybrid systems with virtual cathode, which could radiate due to different radiation mechanisms (bremsstrahlung and diffraction (transition) radiation) with different frequencies.

In vircator systems grid cathode and anode (or anodes) are commonly used [3,4,5,7]. Electron beam oscillates making electrons periodically crossing the grid anodes and cathode (see, for example [5]). It is transition radiation that occur when electrons pass through a border between two media with different indices of refraction. It is worth noting that periodical excitement of transition radiation from electrons oscillating in vircator is similar to diffraction radiation from a charged particle in a periodic structure. As a result in a system with oscillating virtual cathode the vircator radiation, which actually is electron beam bremsstrahlung, is accompanied by radiation excited by additional mechanism due to transition (diffraction) radiation from oscillating current passing through the grid anodes (cathode).

Let us turn to that part of the beam, which passes through the virtual cathode area. Recall that the oscillation of the virtual cathode can produce a highly modulated electron beam, and, as a result, the energy from the bunched transmitted beam can be recovered using slow-wave structures [8].

Interaction of the electron beam with the slow-wave structure in, for instance,
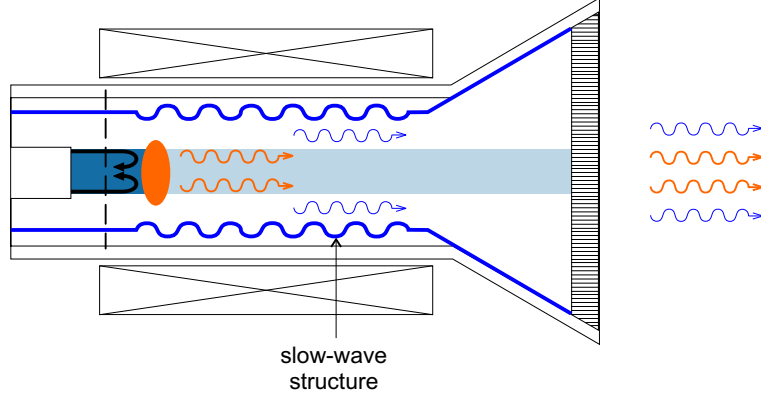
Fig. 2. Hybrid system "vircator + travelling wave tube" [8]

conventional TWT pose special challenges: interaction is sufficiently effective only for electrons moving at the distance δ from the slow-wave structure surface

$$\delta \leq \frac{\lambda\beta\gamma}{4\pi}, \qquad (4)$$

δ is the so-called beam impact parameter, λ is the radiation wavelength, $\beta = v/c$, v is the electron beam velocity, γ is the electron Lorentz-factor. For example, for electrons with the energy 250 keV ($\beta = 0.74$ and $\gamma = 1.49$) and radiation wavelength $\lambda = 10mm$ (frequency 30 GHz) the impact parameter $\delta \approx 0.9mm$. It means that for efficient radiation generation an annular electron beam with the thickness $\Delta \leq \delta$ otherwise only part of the beam would contribute to radiation.

As we have shown in [9,10,11,12,13,14,15,16] this challenge can be overcome applying a photonic crystal, formed by metallic grids (grid travelling wave tube(grid TWT), grid volume free electron laser(grid VFEL)).

What is more, in accordance with [17,18,19] application of metallic inserts (meshes, grids and so on) inside a resonator enables increasing of the electron beam limit current.

Therefore, in the grid TWT (grid VFEL) presence of the metallic grid (photonic crystal) serves both for forming of resonator, where interaction of the beam and radiation occurs, and for potential balancing that makes possible to increase the beam vacuum limit current.

And for the grid TWT (grid VFEL) with the supercritical current the electron beam executes compound motion exciting two radiation mechanisms contributing to radiation: bremsstrahlung of oscillating electrons and diffraction (transition) radiation from downstream electrons interacting with the periodic grid structure(photonic crystal).

This means that the hybrid system "vircator + grid TWT (grid VFEL)" arise by analogy with [8], where several vircators could appear due to presence of several anode grids (see also [3]). But in contrast to the system [3] the hybrid system "vircator + grid TWT (grid VFEL)" uses periodically placed grids with either constant [11,14,15] or variable period [16].

Frequency of diffraction radiation excited by an electron beam in a periodic structure with the period d is determined by the condition

$$\omega - \vec{k}n(k)\vec{v} = \vec{\tau}\vec{v} \, , \tag{5}$$

where $\vec{v}$ is the electron beam velocity, $\vec{\tau}$ is the reciprocal lattice vector ($|\vec{\tau}| = \frac{2\pi p}{d}$), $n(k)$ is the refraction index of periodic structure, p is an integer number ($p = 1, 2, 3, ...$).

When the electron beam velocity $\vec{v}$ is parallel to the reciprocal lattice vector $\vec{\tau}$ (5) reads [12]

$$\omega = \frac{2\pi p \cdot v}{d(1 - \beta n(\omega, k)\cos\theta)} \tag{6}$$

Essentially, photonic crystal in the grid TWT (grid VFEL) is transparent for radiation as well as for electron beam (see Fig.3). Moreover, several diffracted waves could exist in photonic crystal (see Fig.3d) that makes possible to introduce feedback in such a system at the frequency of diffraction radiation and, hence, to couple several hybrid "vircator + grid TWT (VFEL)" generators making a phase-locked source, in which diffracted waves from one photonic crystal (grid resonator) excites oscillations in the neighbor resonators.
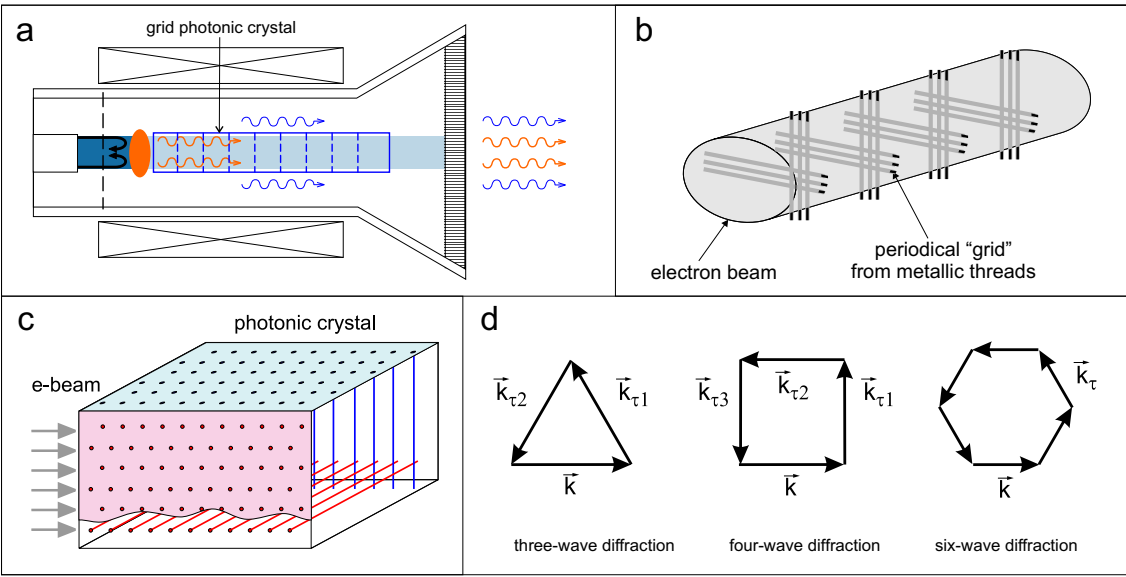

Fig. 3. Grid TWT (grid VFEL) and photonic crystal arrangement

The proposed grid systems drastically differ from the system [3], where several grids serve only for forming of several vircators (see Fig.4).

Of course, radiation from hybrid generator "vircator + grid TWT (VFEL)" can be excited by several electron beams similar phase-locked array.

The bunched electron beam passed through the virtual cathode area can be also used for excitation of free electron laser (ubitron) (see Fig.5) oscillation contributing to the radiation power.
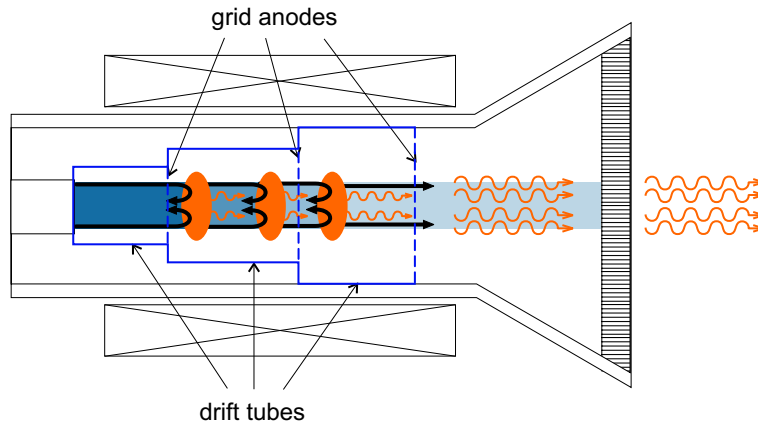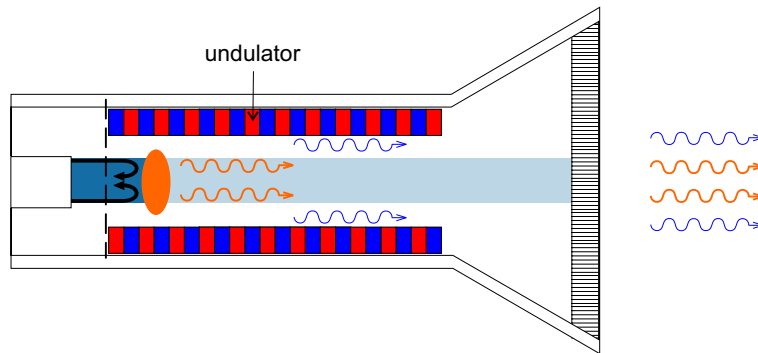
Fig. 4. Several vircators [3]

Fig. 5. Hybrid system "vircator + undulator FEL"

1 Conclusion

It is shown that use of a photonic crystal enables to construct several types of hybrid systems with virtual cathode, which could radiate due to different radiation mechanisms (bremsstrahlung and diffraction (transition) radiation) with different frequencies. Also mentioned that photonic crystal makes possible to create phase-locked array of generators.

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