

Transverse radiation input and output for planar relativistic surface-wave oscillators and amplifiers

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Abstract. Planar surface-wave resonators are very attractive for development of relativistic high-current sources of high-power subterahertz radiation, due to their unique mode selective features. However, evanescent nature of the surface operating wave guided by periodic grating brings a number of difficulties such as wave scattering at the grating edges, power leakage to the cathode, and high ohmic losses. To overcome these problems, we propose using a bi-periodical gratings providing decoupling of the surface wave to the Gaussian microwave beam traveling in the transverse direction. Moreover, the same principle can be used for power input in the relativistic extended-interaction klystron with surface-wave resonators. An analytical quasi-optical theory based on coupled-wave equations are developed for surface-wave resonators with transverse power input-output, as well for planar beam devices based on these resonators. It is shown that the transverse energy extraction significantly reduces the Ohmic losses down to 10% of the radiated power which is essential for sub-THz range. The simulations based on both the quasi-optical model and PIC simulations show that surface-wave oscillator driven by 600 kV, 1 kA could produce 140 MW of output power at 150 GHz with 25% efficiency. For 150 GHz amplifier with the similar beam, simulations predict the 20–40 MW of output power and 20–30 dB linear gain in 1% bandwidth.

Keywords: high-current electronics, high-power microwaves, surface electromagnetic wave, diffraction grating, power output.

1. Introduction

The relativistic high-current devices are most powerful sources of microwave radiation, but their output power decreases when operating frequency increases. It occurs due to decrease of the transverse dimensions of the slow-wave structure (SWS) which results in more stringent microwave breakdown limitations and in decrease of the operating current. To mitigate this power decline, the oversized slow-wave structures are needed. However, in oversize SWSs the problem of mode competition arises.

Relativistic surface-wave oscillators (SWOs) [1–7] are currently considered as promising sources of multi-megawatt power at sub-terahertz waves. In particular, planar version of the SWOs with sheet electron beam is very attractive at sub-terahertz frequencies as far as a usage of evanescent operating eigenmode of the planar slow-wave structure provides ultimate mode selection at least in one transverse direction, namely in the normal direction to the grating plane. However, evanescent nature of the operating wave brings a number of technical difficulties, including scattering of the surface wave at the edges of the grating, power leakage to the cathode region, and high ohmic losses. All these issues decrease the output radiation power and hamper utilizing of generated microwave radiation for applications.

To organize effective and practical radiation output in the planar relativistic high-power surface-wave oscillator, we have recently proposed [8] to apply an additional corrugation with a period twice larger than the period of the main corrugation (Fig.1). This auxiliary grating scatters the evanescent waves into Gaussian beam leaking in perpendicular direction to slow-wave structure. The similar method was studied earlier in distributed feedback lasers for power output and mode selection [9, 10] and in low-voltage clinotron devices for efficient power output and for reduction of ohmic losses [11–13]. In relativistic SWOs, the transverse energy extraction reduces the Ohmic losses drastically and allows avoiding parasitic wave scattering and leakage to the cathode region thus improving the device efficiency. Besides, the Gaussian output beam produced by proposed method is very suitable for further radiation usage in applications.

The same method could be applied for power input in surface-wave amplifier as well [14]. In high-power extended interaction klystron driven by a high-current sheet electron beam and exploiting open gratings as surface-wave cavities, the additional corrugation could provide in- and out-coupling of the radiation in input and output sections, respectively.

2. Simulations and design of surface-wave oscillator with transverse radiation output

We consider relativistic surface-wave oscillator of planar geometry driven by a high-current sheet electron beam and operating at the π -mode of the slow-wave structure, so that the electron-wave synchronism occurs near the frequency of the Bragg resonance, $\omega \approx \bar{h}v/2 \approx \pi c/d$, where ω is the operating angular frequency, $\bar{h} = \pi/d$ is the Bragg wavenumber, d is the grating period, v is the electron velocity, and c is the speed of light. To organize decoupling of the surface wave from the grating, an additional corrugation with twofold period is introduced so that the slow-wave structure form can be describes as, for example,

$$b(z) = b_d \cos(\bar{h}z) + d_{2d} \cos(\bar{h}z/2), \quad (1)$$

where b_d and b_{2d} are the amplitudes of the main and additional corrugations, correspondingly. Resulting slow-wave structure is a shallow bi-periodic grating with the odd grooves being somewhat deeper than the even grooves, see Fig.1. The main (d -periodic) corrugation couples two quasi-optical paraxial TM-polarized wavebeams propagating along the surface in the opposite directions of z -axis under Bragg resonance condition $\omega/c \approx \bar{h}/2$ [15, 16]. The corrugation with the period $2d$ scatters these wavebeams in the normal direction to the plane of the grating, providing the power output. By varying the amplitude of the second corrugation, we can control the resonator quality factor Q . In order to provide the efficient power output, the resulting quality factor should be defined mostly by the transverse wave leakage and should be significantly lower than the ohmic quality-factor Q_{ohm} and quality factor defined by wave scattering at the grating edges, which is proportional to the third power of the grating length [17].

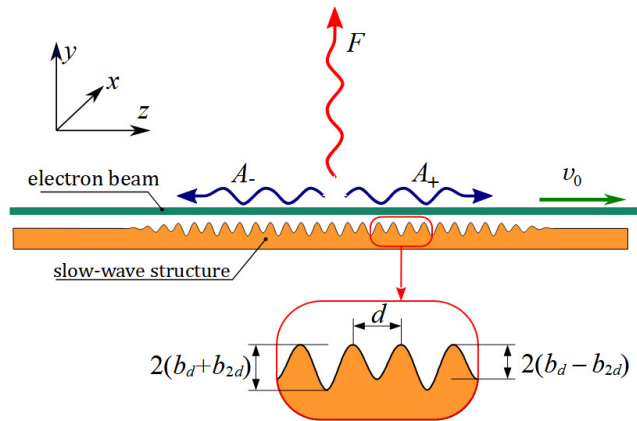


Fig.1. Geometry of the surface-wave oscillator with transverse power output. The inset shows in detail a fragment of the bi-periodic grating.

As an example, we have designed the SWO for 150 GHz operation with the main grating period of $d = 0.835$ mm, amplitude of $b_d = 0.15$ mm, and length of 35 mm. The additional grating have the amplitude of $b_{2d} = 0.06$ mm. The sheet electron beam with 2 cm width have the voltage of 600 kV and current of 1 kA/cm. Beam thickness and distance between the beam and the corrugated surface are assumed to be 0.2 mm. Simulations based on quasi-optical theory [8] and on PIC-code

CST Studio are in perfect agreement and demonstrate that oscillator can operate at the designed mode with electron efficiency up to 25% (Fig.2), while the ohmic losses are less than 10%. In contrast, in the generator without transverse power output the ohmic losses are significantly higher (about of 30% for discussed frequency). The output power of about 140 MW is radiated as Gaussian-like wavebeam (Fig.2), which is convenient for its further transportation and application.

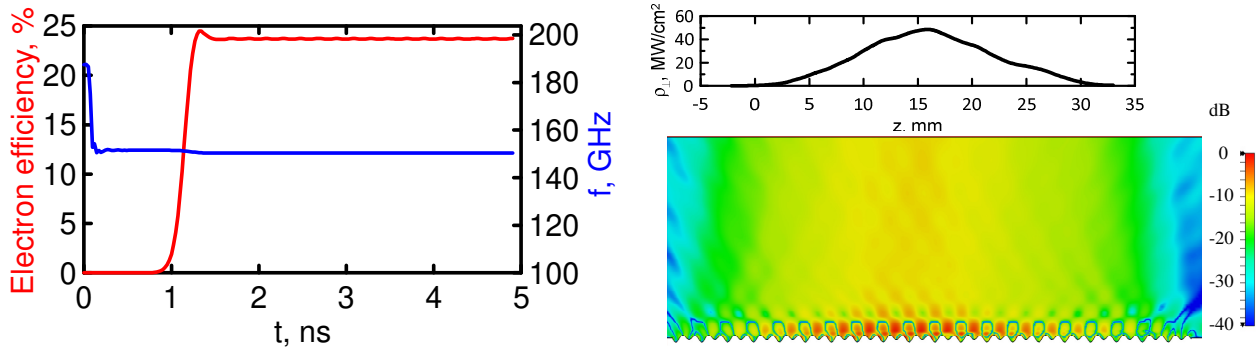


Fig.2. (Left panel) Simulated dynamics of radiation frequency and electron efficiency of SWO with transverse power output. (Right panel) Microwave field structure in the oscillator.

3. Extended-interaction surface-wave klystron with transverse power input-output

The same method could be used as well for power input in surface-wave amplifier [14]. In high-power extended interaction klystron (EIK) exploiting open gratings as surface-wave cavities driven by a high-current sheet electron beam, additional corrugation provides in- and out-coupling of the radiation. For simulated EIK, the beam and grating parameters were chosen close to the parameters used in previous section but an electron energy 0.7 MeV is taken. Lengths of input and output sections are as 10 and 15 mm, respectively, and the Q -factors are 30 and 40. To prevent self-excitation, the 90-mm drift region is partially filled with an absorber. Simulations based on 2D quasi-optical theory [14] and PIC code demonstrate the 20–40 MW of output power in Gaussian beam and 20–30 dB linear gain in 1% bandwidth.

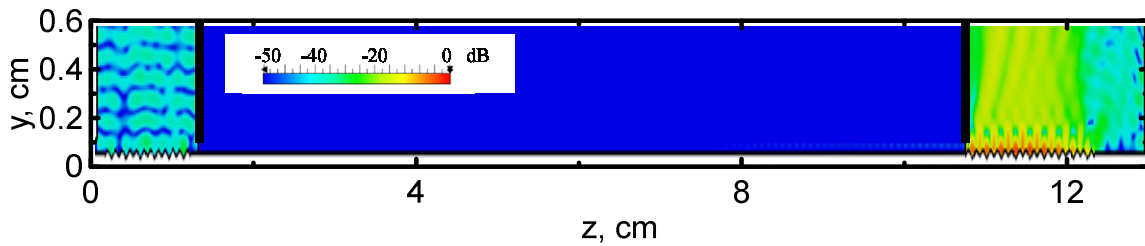


Fig.3. Model of the EIK with surface-wave resonators and transverse power input/output and the microwave field structure in this device [14].

4. Conclusion

For high-current planar surface-wave oscillators and amplifiers, the use of bi-periodic gratings is proposed for providing transverse power output. It is shown that the transverse energy extraction significantly reduces the Ohmic losses in sub-THz frequency range and simplify the microwave power transportation and application. The simulations demonstrate that 150-GHz surface-wave oscillator driven by 600 kV, 1 kA sheet beam could produce hundreds of megawatts of output radiation. The 150 GHz amplifier with similar beam could provide tens of megawatts in 1% bandwidth with 20–30 dB gain.

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5. References

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