激光与光电子学进展
Laser & Optoelectronics Progress

Numerical Simulation of a Double Electron Beam Interaction

Meng Xianzhu

Shandong Provincial Key Laboratory of Optical Communication Science and Technology, School of Physics Science and Information Engineering, Liaocheng University, Liaocheng, Shandong 252059, China

Abstract Double electron beam interaction is studied by numerical simulation method. The simulation results show that when an electron beam (I) composed of many micro-pulses passes close to another electron beam (II) composed of many micro-pulses, the moving spatially periodic electric field of electron beam (II) can force the electrons in the electron beam (I) to follow a curve path, and electromagnetic radiation is stimulated by the acceleration of the electrons in the electron beam (I) along this curve path. In the same way, electromagnetic radiation is stimulated by the acceleration of the electrons in the electron beam (II) along this curve path. This novel electromagnetic radiation generated by double electron beam interaction effect is called double electron beam interaction radiation in this paper. Using a quasi optical resonator, coherent double electron beam interaction radiation with a high output peak power can be obtained.

Key words lasers; double electron beam interaction; electromagnetic radiation; quasi optical resonator
OCIS codes 230.3990; 230.6080 ; 350.4010; 350.5610

对双电子束互作用的数值模拟

孟现柱

聊城大学物理科学与信息工程学院山东省光通信科学与技术重点实验室，山东 聊城 252059

摘要 利用数值模拟的方法对双电子束互作用进行了研究。结果显示：当一束由许多微脉冲组成的电子束(I)紧贴另一束由许多微脉冲组成的电子束(II)运动时，电子束(II)产生的移动的空间周期性电场能够迫使电子束(I)中的电子做曲线运动，使电子束(I)中的电子做曲线运动的加速度将会使电子产生电磁辐射。同理，使电子束(II)中的电子做曲线运动的加速度将会使电子产生电磁辐射。把这种由于双电子束互作用产生的辐射称为双电子束互作用辐射。利用准光学谐振腔，可以得到高峰值功率的相干双电子束互作用辐射。

关键词 激光器；双电子束互作用；电磁辐射；准光学谐振腔
中图分类号 O436 **文献标识码** A **doi**: 10.3788/LOP51.072301

1 Introduction

When an electron beam passes through a succession of electric or magnetic field of alternating polarity, the electrons in the beam are forced to follow a curve path, and photons are emitted by the acceleration of the electrons along this curve path, just like free electron laser (FEL). In the FEL, when the beam passes through the FEL oscillator (a magnetic structure, this magnetic structure is sometimes called an undulator, or a wiggler), the FEL oscillator forces the electrons in the beam to follow a sinusoidal path[1-4]. The acceleration of the electrons along this sinusoidal path results in the release of photons.

In this paper, we investigate a double micro-pulse electron gun structure to produce a spatially periodic electric or magnetic field to force the electrons beam to follow a curve path. This device is studied by theoretic analysis and numerical simulation method. The results show that when an electron

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收稿日期: 2014-02-01; **收到修改稿日期**: 2014-02-11; **网络出版日期**: 2014-06-18
基金项目: 国家自然科学基金(11275089，11375081)、山东省自然科学基金(ZR2011FQ001)

作者简介: 孟现柱(1968—)，男，硕士，副教授，主要从事史密斯-帕塞尔辐射方面的研究。E-mail: mengxz@lcu.edu.cn beam composed of many micro - pulses passes close to another electron beam composed of many micro-pulses, a novel electromagnetic radiation is stimulated. Using a quasi optical resonator, coherent double electron beam interaction radiation with a high output peak power can be obtained.

2 Research content

2.1 Theoretical analysis of double electron beam interaction radiation

Micro-pulse electron gun (MPG) is a novel microwave electron gun[5-6]. It is a type of high brightness electron source. The electron beams with pulse width up to microseconds, or even hundreds of microseconds can be obtained by MPG. This electron beam is often called macro-pulse. Usually, the macro-pulse is composed of many electron bunches with pulse width of a few picoseconds, or even tens of femtoseconds, this electron bunch is often called micro-pulse [7]. The time structure of pulses of the electron beam from MPG is shown in Fig.1, where F is macro-pulse repetition frequency, T is macro-pulse width, f is micro-pulse repetition frequency, τ is micro-pulse width.

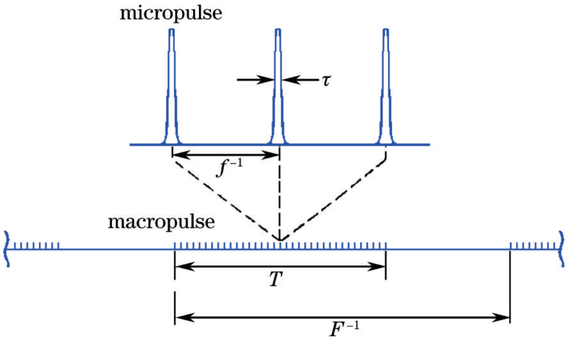

Fig.1 Time structure of pulses of electron beam from micro-pulse electron gun

When an electron beam composed of many micro- pulses moves through a space, a moving spatially periodic electric and magnetic field will be produced in this space. The repetition frequency of this moving spatially periodic electric and magnetic field is equal to micro-pulse repetition frequency. The moving spatially periodic electric field can force the electrons in the space to follow a curve path, and photons are emitted by the acceleration of the electrons along this curve path.

To generate an electron beam composed of many micro-pulses to force the electrons in another electron beam to follow a curve path, we investigate a double MPG structure. The double MPG structure is composed of two MPGs. Every MPG can produce high brightness electron beam composed of many micro- pulses. When an electron beam (I) composed of many micro- pulses passes close to another electron beam (II) composed of many micro- pulses, the moving spatially periodic electric field of electron beam (II) can force the electrons in the electron beam (I) to follow a curve path, and electromagnetic radiation is stimulated by the acceleration of the electrons in the electron beam (I) along this curve path. In the same way, the moving spatially periodic electric field of electron beam (I) can force the electrons in the electron beam (II) to follow a curve path, and electromagnetic radiation is stimulated by the acceleration of the electrons in the electron beam (II) along this curve path. This novel electromagnetic radiation generated by double electron beam interaction effect is called double electron beam interaction radiation in this paper.

2.2 Numerical simulation of double electron beam interaction radiation

By the particle-in-cell (PIC) simulation method, the characteristics of the double electron beam interaction radiation can be studied. The PIC simulation is performed with the CHIPIC code, which is a finite-difference time-domain (FDTD) code for simulating processes involving interactions between space charge and electromagnetic field[8-9]. The FDTD method can solve complicated problems[10-12]. With the help of the PIC simulation, the characteristics of the double electron beam interaction radiation including the radiation energy and the field distribution as well as the interaction processes of electron bunches with the target can be observed. The main parameters are summarized in Table1. The simulation geometry is shown in Fig.2.

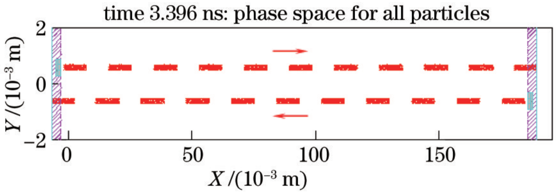

Fig.2 Simulation geometry of double electron beam interaction at 3.396 ns

Table 1 Parameters of the simulations

Parameters	Value
Beam voltage	100 kV
Current density	50 A
Radius of beam	0.3 mm
Micro - pulse repetition frequency	9×10^9 Hz
Axial magnetic field	2.0 T

Figure3 shows the profile distribution of field energy in $x-y$ plane of the double electron beam interaction radiation. In Fig.3, a contour map of the electromagnetic field components E_x, E_y, E_z, B_x, B_y and B_z in the $x-y$ plane at time t=3.396 ns is displayed. According to electromagnetic theory, only electromagnetic field components E_x, E_y, and B_z should be produced in the $x-y$ plane as the electron beam pass along z axis in this space. But according to Fig.3, we can see that the electromagnetic field components E_z, B_x, and B_y are also produced in the $x-y$ plane, and the distribution of electromagnetic field components E_z, B_x, and B_y display regular distribution. The regular distributions show that high frequency electromagnetic field (HFEMF) can be generated by double electron beam interaction effect in the simulation space. This simulation results show that when an electron beam composed of many micro- pulses passes close to another electron beam composed of many micro- pulses, a novel electromagnetic radiation is stimulated. This novel electromagnetic radiation is due to double electron beam interaction rather than two-stream instability. In this device, the micro-pulses are equivalent to the FEL oscillator. When an electron beam (I) composed of many micro-pulses passes close to another electron beam (II) composed of many micro - pulses, the electron beam (II) can force the electrons in the electron beam (I) to follow a curve path. The acceleration of the electrons along this curve path results in the release of photons.

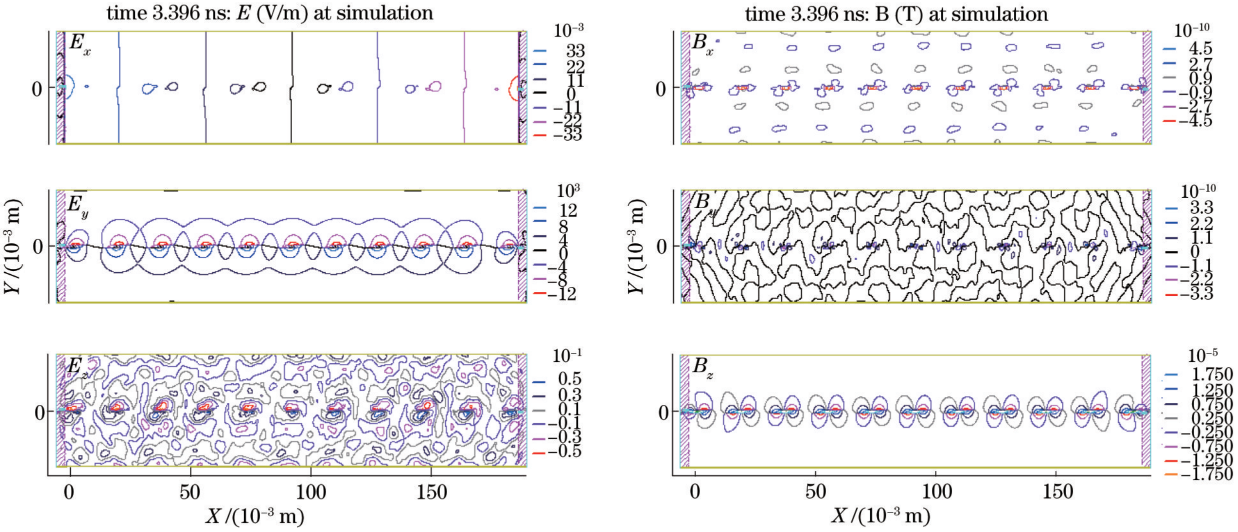

Fig.3 Profile distribution of field energy of the double electron beam interaction radiation at 3.396 ns

The evolution curve of field power S.DA of the double electron beam interaction radiation and the corresponding FFT at the output port are shown in Fig.4. Apparently, there exist a lot of different types of radiation. One is a fundamental wave originated from the double electron beam interaction radiation, whose frequency is equal to micro- pulse repetition frequency (9×10^9 Hz). Another is the harmonic originated from the double electron beam interaction radiation too, whose frequency is $2\times9\times10^9$ Hz and etc. The results show that the frequency of the double electron beam interaction radiation is strongly dependent on the micro-pulse repetition frequency.

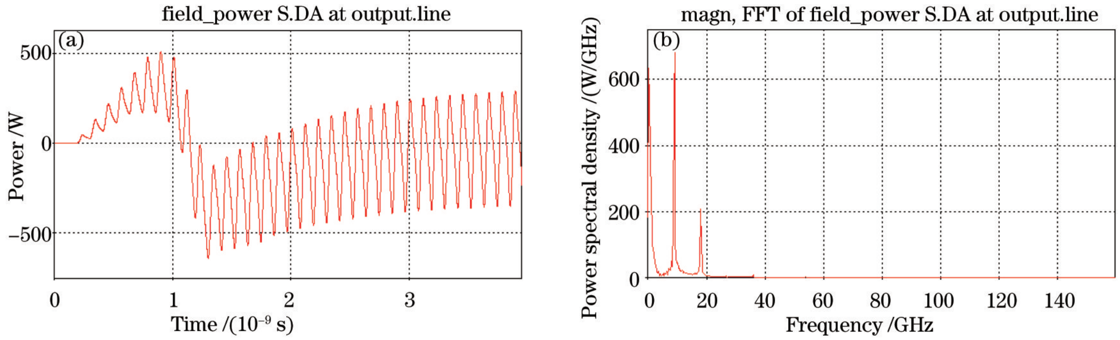

Fig.4 Evolution curve of field power of the double electron beam interaction radiation. (a) Field power S.DA; (b) corresponding FFT

2.3 Numerical simulation of coherent double electron beam interaction radiation

Usually, the double electron beam interaction radiation is too weak to be used and the detection of the signal is very difficult. To generate coherent radiation, a feedback configuration such as quasi optical resonator is utilized. As shown in Fig.5, the quasi optical resonator is composed of two mirrors whose material is conductor. In the quasi optical resonator, when an electron beam (I) composed of many micro-pulses passes close to another electron beam (II) composed of many micro-pulses, the double electron beam interaction radiation is stimulated. The quasi optical resonator could reflect the radiation back into the electron beam. When the radiation is reflected back into the electron beam, the electron beam can be modulated. If the proper conditions of synchronism are met, the electron beam is bunched and the radiation is gained gradually [13-14].

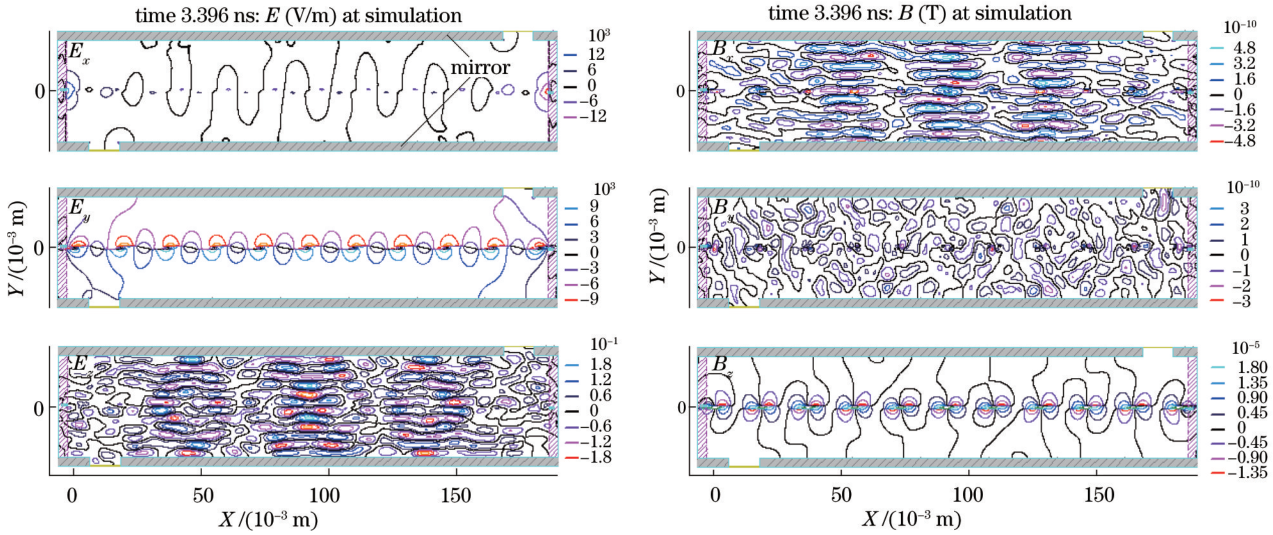

Fig.5 Profile distribution of field energy of coherent double electron beam interaction radiation at 3.396 ns

Figure5 shows the profile distribution of field energy in $x-y$ plane of the coherent double electron beam interaction radiation. In Fig.5, a contour map of the electromagnetic field components E_x, E_y, E_z, B_x, B_y and B_z in the $x-y$ plane at time t=3.396 ns is displayed. We can see that the distribution of electromagnetic field components E_z, B_x, and B_y display regular distribution. Compare Fig.5 and Fig.3, we note that a more regular distribution of electromagnetic field components E_z and B_x in Fig.5 is displayed. This more regular distribution is due to beam-wave interaction. And this kind of filed distribution is beneficial to improve beam-wave interaction. Since beam-wave interacts steadily, the more regular distribution of electromagnetic field components E_z and B_x has increased second by second. The simulation results show that when the interaction reaches self-exciting condition, a steady state oscillation can be established at one of the resonant frequencies of the quasi optical resonator, and coherent radiation can be generated. The condition of coherent radiation is due to the micro-pulse repetition frequency and the resonant frequencies of the quasi optical resonator. By adjusting the micro-pulse repetition frequency, or adjusting the quasi optical resonator, tunable coherent double electron beam interaction radiation can be observed.

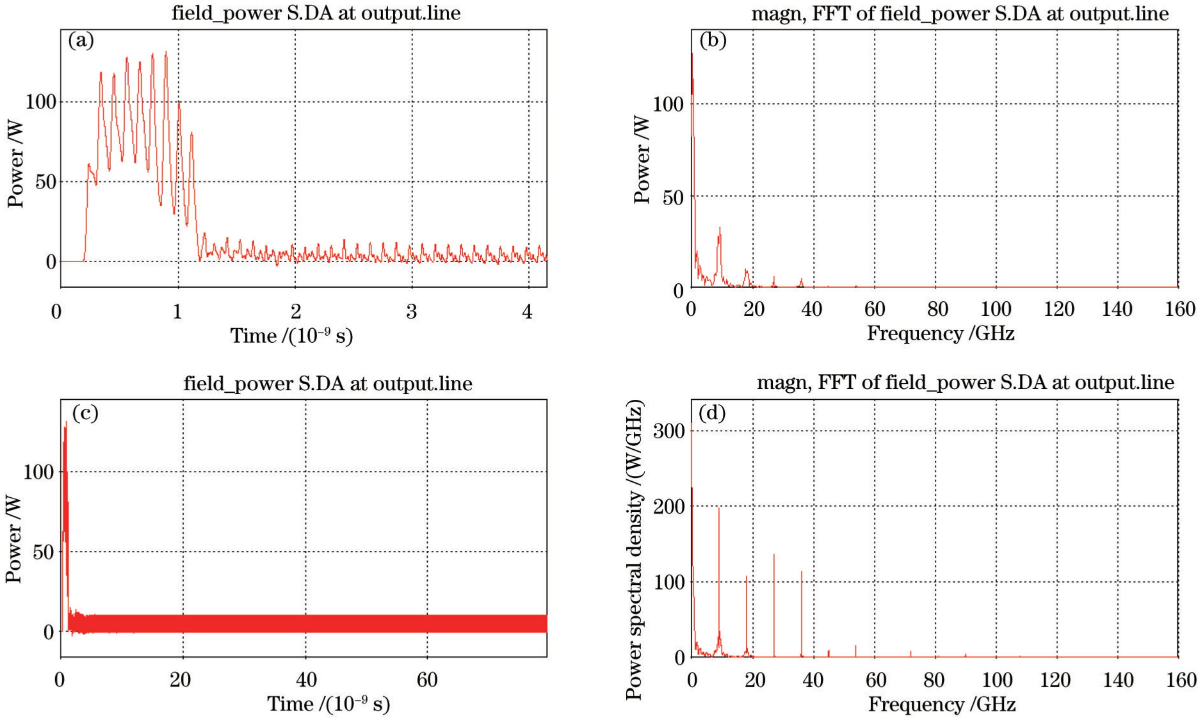

Fig.6 Evolution curves of field power coherent double electron beam interaction radiation at output port. (a) Field power S.DA at output port in 4.15 ns; (b) corresponding FFT at output port in 4.15 ns; (c) field power S.DA at output port in 79.6 ns; (d) corresponding FFT at output port in 79.6 ns

The evolution curve of field power S.DA of coherent double electron beam interaction radiation and the corresponding FFT at the output port are shown in Fig.6. Apparently, there exist a lot of different types of radiation. One is fundamental wave originated from the coherent double electron beam interaction radiation ,whose frequency is equal to micro-pulse repetition frequency (9×10^9 Hz). Others are the harmonics originated from the coherent double electron beam interaction radiation too, whose frequency is $2\times9\times10^9$ Hz, $3\times9\times10^9$ Hz and etc. Comparing Fig.6(b) and Fig.6(d), we note that as the beam-wave interaction reaches self-exciting condition, the radiation field begins to increase rapidly. In Fig. 6 (d), from the FFT amplitude, the dominant radiation is the fundamental wave and the third harmonic (9×10^9 Hz, $3\times9\times10^9$ Hz).

3 Conclusion

It can be concluded from the simulation results that when an electron beam (I) composed of many micro-pulses passes close to another electron beam (II) composed of many micro-pulses, a novel electromagnetic radiation is stimulated. This novel electromagnetic radiation is generated by double electron beam interaction effect. Using a quasi optical resonator, coherent double electron beam interaction radiation with a high output peak power can be obtained.

Finally we should note that the double micro-pulse electron gun structure is a promising candidate for developing a more compact, less complex FEL compared with conventional oscillator FEL.

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