Experimental Study of Coaxial Free-Electron Maser Based on Two-Dimensional Distributed Feedback

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The first experimental study of a coaxial free-electron maser (FEM) based on two-dimensional (2D) distributed feedback is presented. A new type of cavity formed with coaxial 2D surface photonic band gap structures was used. The FEM was driven by a large diameter (7 cm), high-current (500 A), annular electron beam of energy 475 keV. By tuning the amplitude of the undulator or guide magnetic field, modes associated with the different band gaps of the 2D structures were excited. The Ka-band coaxial FEM generated 15 MW of radiation with a 6% conversion efficiency, in excellent agreement with theory.

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Gigahertz, terahertz and optical devices with distributed feedback are promising sources of high-power electromagnetic radiation. Indeed, oscillators and passive devices using one-dimensional (1D) distributed feedback, which can be realized inside a 1D periodic lattice [1D Bragg structures, or 1D photonic band gap (PBG) structures], have been under intense investigation for the last 40 years and such 1D structures have been applied successfully in many branches of physics including vacuum electronics, integrated, and nonlinear optics [1–3]. To further increase the power of the radiation sources, new methods are required to reduce the power density of the electromagnetic radiation confined inside the interaction region. Increasing the power, without changing the dimensions of the interaction space, can result in an increase in the electromagnetic field power density inside the cavity to a threshold value, above which operation of the oscillator can be detrimentally affected [4]. One attractive solution is to increase the transverse size of the cavity to enable the power density to be kept below this threshold value. However, this may lead to a decline in cavity mode selectivity along the wave transverse index, resulting in a multimode stochastic regime of operation [5]. To maintain the mode selectivity along the longitudinal and one of the transverse coordinates the use of 2D distributed feedback has been proposed [6]. However, a limitation in the cavity dimension along the second transverse coordinate still applies. The use of a coaxial cavity enables the distance between the inner and outer conductors to remain small while allowing an increase in the circumference of the cavity and therefore the diameter of the electron beam propagating through the system. Currently oscillators based on 2D distributed feedback are under intensive theoretical and experimental investigation [7,8]. Such distributed feedback can be obtained inside 2D surface photonic band gap (SPBG) structures [9,10]. In contrast with the 1D structures the "forward" and "backward" propagating waves are coupled indirectly via partial waves, which are associated with near cutoff waves of the waveguide. Such an indirect coupling of the forward propagating wave that interacts with the electron beam with the backward propagating wave allows radiation from the different parts of the oversized active medium to be synchronized [5–9]. To observe the effective wave coupling on the corrugation, the Bragg conditions should be simultaneously satisfied for each pair of coupled waves [9], which ensures the mode selectivity along the transverse index. In this Letter we report the first operation of a coaxial free-electron maser (FEM) driven by a 7 cm diameter oversized (with respect to the operating wavelength) thin (2 mm) annular electron beam, which used a two-mirror cavity (Fig. 1) defined by 2D SPBG structures. The results obtained are the first experimental proof that the concept of 2D distributed feedback can be used in oversized coaxial systems to achieve selection of the wave transverse index. These results are relevant to many other branches of physics, which use distributed feedback and periodical lattices in wave matter interactions.

Theoretical study of the dynamics of coaxial FEMs with 2D SPBG structures [7,8] together with microwave measurements of the 2D SPBG structures [9,10] enabled the cavity's parameters to be chosen, which minimized both the transition time and the starting current required for oscillation. Based on analysis of the results obtained, the cavity (Fig. 1) was chosen to have the following parameters: length of the input and output mirrors $L_1 = 10.4$ cm

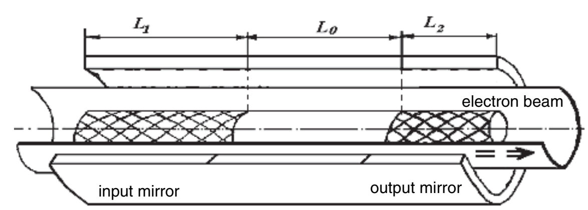

FIG. 1. The schematic of the two-mirror cavity formed with the 2D surface photonic band gap structures of length $L_1 = 10.4$ cm, $L_2 = 5.6$ cm, and smooth coaxial waveguide of length $L_0 = 65$ cm.

and $L_2 = 5.6$ cm, respectively, length of the smooth coaxial waveguide $L_0 = 65$ cm, period of corrugation of the structures 0.4 cm, and number of the azimuthal variation of the corrugation 24. Taking into account the cavity parameters, it was estimated that the transition time should not exceed 150 ns if the driving electron beam current exceeds 200 A.

Two-dimensional structures were used in the experiment to define the two-mirror cavity with the overlap of the band gaps of these structures defining the frequency band of FEM operation. In the experiment the central frequencies of the input and output mirrors coincided with the operating frequency range defined by the structure with the narrowest band gap, in this case defined by the output mirror. The results of the experimental measurements of transmission of the azimuthally symmetric TEM wave through the output (5.6 cm) mirror is presented in Fig. 2. The center of the band gap is about 37.2 GHz with the reflection coefficient −20 dB at the center frequency. The width of the band gap is associated with the wave-coupling coefficient α [9,10], which depends on the structures of the waves coupled and the geometric parameters of the 2D SPBG structure. For the experiments conducted the wave-coupling coefficient was estimated to be about 0.14 cm^{-1}, if TEM waves are coupled, which corresponds to the band gap width of ~0.4 GHz. Such structures also have band gaps associated with the coupling of other modes, and the nearest band gap is associated with coupling of forward and backward $\text{TE}_{1,0}$ waves and is located around 39.3 GHz [9,10]. Therefore if the system parameters are optimum for excitation of this nonsymmetric wave then oscillation around 39.3 GHz would be expected.

To drive the FEM, a high-current accelerator based on a magnetically insulated annular plasma flare emission carbon cathode and a cylindrical anode was used. A Marx bank power supply resonantly charged a deionized water-filled transmission line up to 1 MV, the output of which was switched across the cathode and anode using a high pressure spark gap, resulting in ~200 ns duration, 475 kV accelerating voltage pulse being applied across the anode and cathode Fig. 3(a). For an accelerating voltage of 475 kV, a thin (0.2 cm) annular electron beam (~0.5 kA) of mean diameter 7.0 cm was produced and transported through the coaxial transmission line of length ~2 m with diameters of inner and outer conductors of 6 and 8 cm, respectively. Mylar witness plate diagnostics were used to align the electron beam. The azimuthally symmetric undulator of period 4 cm located inside the uniform magnetic guide field was used to pump the transverse electron oscillation. The undulator field was slowly tapered up over the initial 6 periods ensuring the adiabatic entrance of the electron beam inside the interaction space. The amplitude of the undulator could be varied to up to 0.06 T while the amplitude of the guide magnetic field could be changed up to 1 T. The two-mirror cavity was located inside the uniform part of the undulator. An electron beam current of 500 A was measured using a Rogowski coil and is presented in Fig. 3(b). To meet resonance conditions, i.e., $\omega = (k_z + k_u)\nu_\parallel$ where k_z is the longitudinal wave index, $k_u = 2\pi/d_u$, $d_u = 4$ cm is the undulator period, and $\nu_\parallel$ is the electron beam longitudinal velocity, and to maximize the FEM gain, the 2D time dependent particle-in-cell code KARAT has been used to simulate the FEM operation in the self-amplification of spontaneous emission regime. In this regime the noise naturally existing inside the interaction region was amplified, and the output signal was used to optimize FEM operation with respect to different values of the guide and undulator magnetic fields. The spectrum of the electromagnetic radiation was studied, and it was observed that for specific parameters of the undulator and

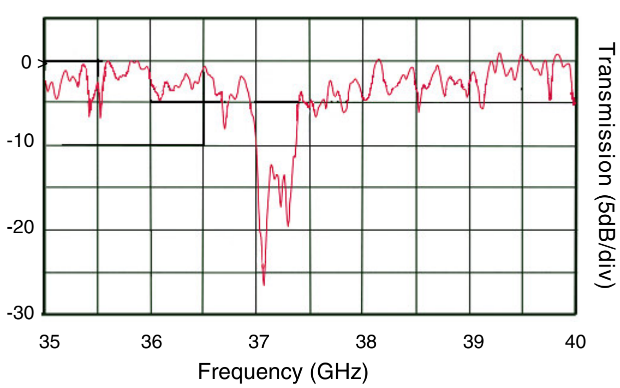

FIG. 2 (color online). The results of the experimental study (transmission coefficient) of the 2D SPBG structure, which is used as an output mirror of the two-mirror cavity.

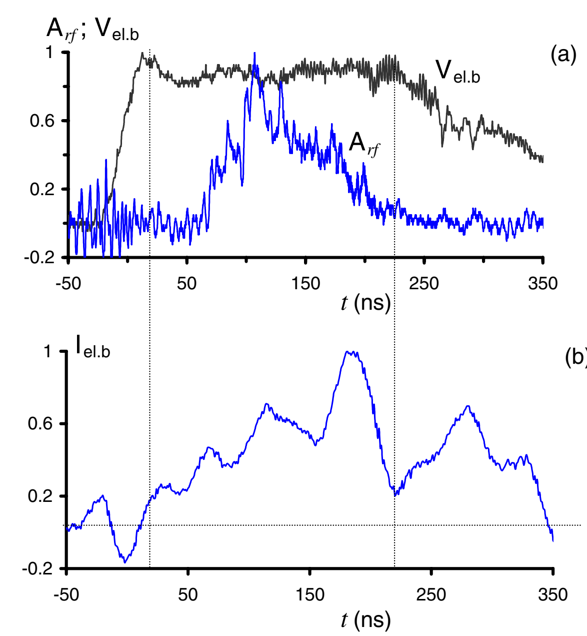

FIG. 3 (color online). The trace of the (a) electron beam voltage ($V_{\text{el},b}$) and RF output pulse (A_{rf}). (b) The trace of the electron beam current measured with Rogowski coil ($I_{\text{el},b}$).

guide magnetic fields a TEM wave at the frequency of 37.2 GHz was strongly amplified. It was also observed that variation in the amplitude of the undulator field or the guide magnetic field resulted in variation of the amplified frequency.

In these first experiments well-defined and reproducible microwave pulses were generated (with ±10% shot-to-shot variation in power and pulse width, as well as constant spectrum) if the conditions were maintained the same. In Fig. 3(a) the trace of the microwave pulse in comparison with the traces of the electron beam voltage and electron beam current are presented. It is clearly evident that the oscillation takes place after some transition time of ~100 ns and it terminates when the electron beam voltage decreases after ~200 ns. To measure the output radiation (A_{rf}) from the FEM, two *Ka*-band (26.5 to 40 GHz) receiving horns with 55 dB of attenuation in conjunction with HP8474E (0.01–50 GHz) detectors were located at a distance of 1.5 m from the output window. The first horn was "fixed" at the same position during all the experiments to provide a reference signal. The position of the second horn was free to move and was used to study the output radiation characteristics. The output radiation pattern from a conical coaxial horn of inner and outer diameters 3 and 19 cm, respectively, was measured. The pattern measured in the hot experiments, when an electron beam was present, was compared with the radiation pattern when the horn was excited by a TEM wave of frequency 37.2 GHz and theoretical data obtained from numerical simulations using the electromagnetic solver embedded in the 3D code MAGIC (Fig. 4). The output power measured at the detector was integrated over the measured radiation pattern resulting in an FEM output power of 15 MW, which corresponded to ~6% efficiency. The relative uncertainty of the power measured during experiment did not exceed 10%. The frequency of the output radiation was measured using a heterodyne frequency diagnostics. Microwave radiation from the FEM was mixed in a nonlinear Farran Technology waveguide balanced mixer BMC-28B. The calibration of the mixer was confirmed in the frequency range 26.5 to 40 GHz in cold microwave measurements using a 40 GHz Hewlett-Packard synthesized sweeper acting as the local oscillator and an Anritsu pulsed sweeper that could produce a 100 ns duration millimeter wave pulse in the frequency range 0.01–50 GHz to act as the microwave source to be measured. The Anritsu swept source was replaced with the output signal from the 2D Bragg FEM. The resultant intermediate frequency captured on a deep memory Le Croy digitizing oscilloscope was measured. Knowing the frequency of the local oscillator (LO) and ensuring that the signal to be measured was located within a frequency of 1.5 GHz (digitizing bandwidth of oscilloscope) from the LO, measurement of the resultant intermediate frequency enabled the output frequency of the FEM to be ascertained. In experiments at a local oscillator frequency of 38 GHz the resultant intermediate frequency was recorded, and by taking the fast Fourier transform of the intermediate frequency the spectrum of the mixed signal was plotted in Fig. 5. In Fig. 5 the traces of the microwave pulses and corresponding spectra of the microwave signals are presented. In addition, cutoff filters were used to establish that the 2D Bragg FEM operated within the 36.9 to 40 GHz frequency region. The heterodyne frequency diagnostic was used to study frequency tuning of the 2D Bragg FEM as the undulator and solenoid magnetic field were varied. Tuning the amplitude of the

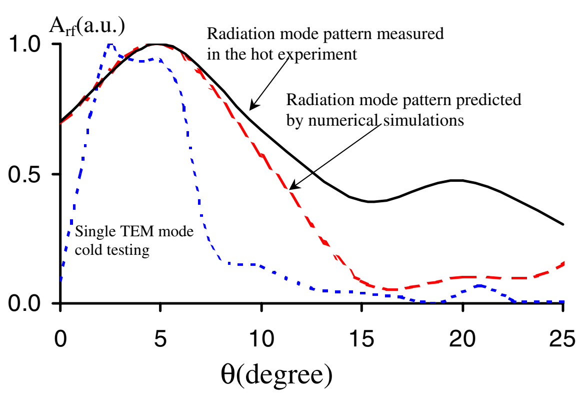

FIG. 4 (color online). The output radiation mode pattern mapped in the "cold" study (dotted line) of the horn and during the "hot" experiments (solid line) and observed from numerical simulations (dashed line).

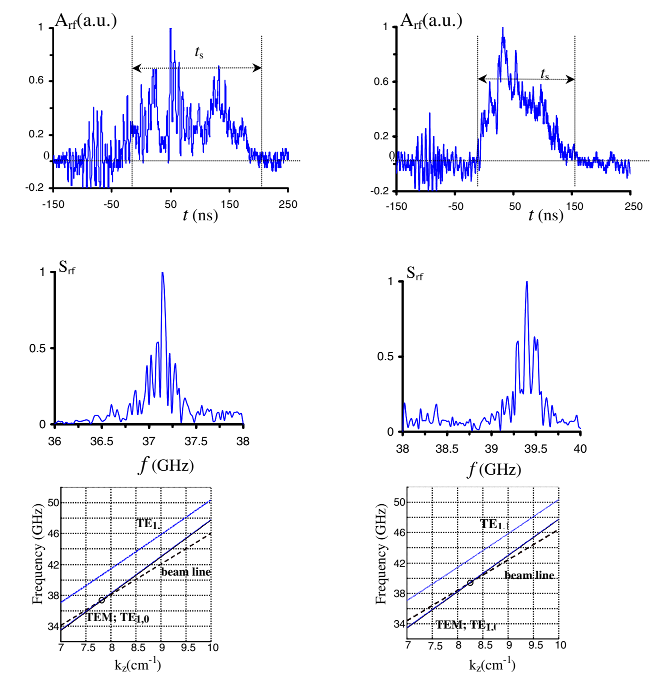

FIG. 5 (color online). The shape and the spectrum of the output RF pulse and the dispersion diagram, when (first column) the guide field was (0.6 T, 13.5 kV) and the undulator field (0.06 T, 3 kV) and (second column) the guide field was (0.5 T, 11.5 kV) and the undulator field (0.03 T, 1.5 kV).

guide magnetic field and undulator field two frequency regions around 37.2 and 39.4 GHz associated with the frequency bands of the 2D SPBG structures were measured. When the amplitude of the undulator field was large enough to produce electrons with a pitch factor of ~0.17 the excitation of the TEM azimuthally symmetric mode associated with the first band gap of the structure (37–37.4 GHz) was observed (Fig. 5, first column). The decrease of the undulator field, i.e., the decrease of the pitch factor resulted in an upshift of the operating frequency into a region associated with the second band gap at 39.3–39.6 GHz associated with excitation of the first azimuthally nonsymmetric wave $TE_{1,0}$ (Fig. 5, second column). A further decrease of the undulator field led to the disappearance of the microwave signal. In all experiments conducted a single spectrum line above the pedestal was observed of a width that correlated well with the width of the band gap. The lines of reduced amplitude adjacent to the main spectral line, clearly evident in Fig. 5, can be associated with the transition processes inside the cavity. More detailed analysis of the spectrum is outside the scope of this Letter and will be presented in future work.

In summary the first lasing of an FEM, driven by oversized annular electron beam and using 2D surface photonic band gap structures, has been observed. The experimental studies of the novel FEM have been conducted. The operation of the FEM was observed in two different frequency regions, which are well defined by the band gap parameters of the 2D SPBG structures used. In the experiments a TEM wave mode pattern from the output horn was observed with a measured output power of ~15 MW, which corresponds to ~6% efficiency. The results obtained correspond well with theoretical predictions made in previous work [7]. In these first experiments a high-Q cavity was used, which restricted the efficiency. Decreasing the cavity Q factor in accordance with numerical simulations should result in an increase in efficiency, which will be the next goal of the future experiments. Experimental operation of the coaxial 2D Bragg FEM demonstrates the proof of the concept, namely, that an oversized active device with 2D distributed feedback can be used to achieve mode selection over the transverse index. The results are relevant to several other branches of physics including integrated optics, photonics, and signal processing where distributed feedback is widely used.

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