Radiation beam steering by cyclotron-resonance maser array

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A concept of power beaming by a cyclotron-resonance maser (CRM) array is presented theoretically. In this scheme, the CRM-array operates as an active phased-array antenna, and radiates directly from its output aperture. The gain and phase of each CRM element in the array are controlled by the voltage and current of its electron gun. The consequent phase difference between the CRM-element outputs enables the steering of the radiation beam in the far field. A simplified linear model is presented for a CRM-array antenna with uncoupled elements. It provides radiation patterns which demonstrate the main feature of power-beam steering. A wide angular steering range (±35°) is obtained by an analog electronic control of the CRM array. The feasibility of practical CRM-array antennas is discussed. [S1063-651X(99)01402-6]

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I. INTRODUCTION

Cyclotron-resonance masers (CRMs) and gyrotrons [1,2] are well known as high-power microwave sources. A typical CRM device employs a single high-energy electron beam. The multibeam CRM array was proposed recently as a scheme in which many low-power CRM elements coupled together combine a high-power radiation beam in space [3]. The CRM array consists of many low-energy electron beams propagating in a multichannel lattice waveguide. A linear model of the CRM-array interaction was presented in Ref. [4], and the first experiments were described in Ref. [5]. A stagger-tuned multibeam gyroklystron was proposed and analyzed as a wideband amplifier [6]. This report presents an advanced feature of the CRM array, as an active phased-array antenna with electronic steering abilities.

Power beaming, as a concept of launching directed high-power energy to space, is attractive in areas like communication, radar systems, and plasma heating for fusion [7]. This concept is also explored for military purposes like directed energy weapons [2], and for energy transfer to distant targets [8,9].

Phased-array antennas are usually known as passive devices [10]. They are fed by external microwave sources. The radiation is divided to the radiating elements, usually through Ferrite phase shifters. The radiation steering is accomplished by varying the phase shifts between the elements. Active phased-array antennas consist, in general, of many power-amplifier elements, each of them is tuned to a proper phase in order to build the required far-field radiation lobe, as in Ref. [11]. Similar devices were developed on the basis of traveling-wave-tube multibeam arrays, and of solid-state amplifier arrays [12]. Angular-steering in free-electron laser arrays was proposed and studied as well [13].

The concept of a CRM-array antenna is presented in this paper. The device consists of many CRM elements, all sharing the same axial magnetic field [14]. A conceptual scheme of the CRM-array antenna is shown in Fig. 1. The input electromagnetic (em) wave is injected equally to all the CRM elements in the array. The angular steering of the far-field radiation is accomplished by varying the amplitude and phase of each CRM element. This is done by controlling the accelerating voltage and the electron current of each electron beam in the array.

II. LINEAR MODEL

A simplified CRM-array antenna model is derived in this section in order to demonstrate the concept. The gain and phase variation at the CRM output depend on the physical operating parameters of each element; the em wave frequency (ω), the axial magnetic field (B_{0z}), the electron accelerating voltage (V_{eb}), and current (I_{eb}), and the waveguide structure. In this preliminary study, we assume that the CRM elements in the array are not coupled by the waveguide structure.

A linear analysis of the CRM interaction results in a known Pierce-type gain-dispersion relation [15], applicable for the nth element in the uncoupled array as

$$\tilde{A}_n(\hat{s}) = \frac{(\hat{s}-\hat{\theta}_n)^2}{\hat{s}(\hat{s}-\hat{\theta}_n)^2 - Q_n(\hat{s})} A_0, \tag{1}$$

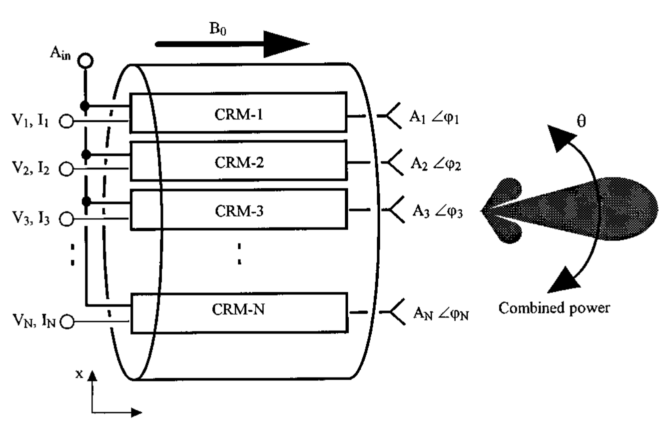

FIG. 1. A conceptual scheme of the CRM-array antenna.

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TABLE I. CRM-array parameters.

Axial magnetic field B_{0z}	2.57 kG
Frequency f	8.2 GHz
Electron beam current I_{eb}	0.5–1.5 A
Electron beam voltage V_{eb}	8–25 kV
Pitch ratio $V_\perp/V_z$	1
Interaction length L	1 m
Number of elements N	10, 25
Phase difference between neighbor elements $\Delta\varphi$	0°, 30°, 60°
Maximum steering angle θ	0°, 17°, 35°

where A_0 and $\tilde{A}_n(\hat{s})$ are the input and output fields, respectively, of the nth CRM element, and $\hat{s}$ denotes the normalized Laplace transform variable. The normalized tuning parameter is $\hat{\theta}_n=(\omega-\omega_{c,n}-\beta\overline{V}_{0z,n})\tau_{0,n}$, where $\tau_{0,n}=L/\overline{V}_{0z,n}$ is the electron time of flight along the interaction region, L. The em wavenumber $\beta(\omega)$ is determined by the waveguide dispersion relation. The cyclotron frequency is $\omega_{c,n}=(e/\gamma_n m_0)B_{0z}$. The gain parameter Q_n depends on the nth electron beam current and energy, and on other parameters as described in Ref. [15].

Assuming that each CRM element radiates from a separate rectangular aperture (TE_{10} mode), and is not coupled to the other elements, the broadside far-field radiation of the nth element is the aperture Fourier transform [10], $f_x^{(n)}(k_x)=\int_x E_x^{(n)}e^{jk_x x}dx$, where k_x is the wave number component in the x direction, and $E_x^{(n)}$ is the electric field profile on the aperture. For the entire CRM-array antenna, the total far-field radiation is the sum

$$F_x(k_x)=\sum_{n=1}^{N} f_x^{(n)}(k_x)A_n e^{j(nk_x d-\varphi_n)}, \tag{2}$$

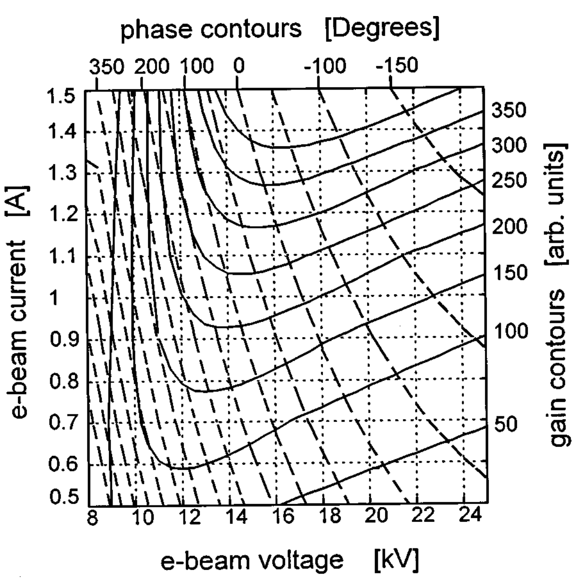

FIG. 2. Gain and phase contours of a single CRM element for the parameters listed in Table I. The solid and dashed lines are gain and phase contours, respectively, vs the electron-gun voltage and current.

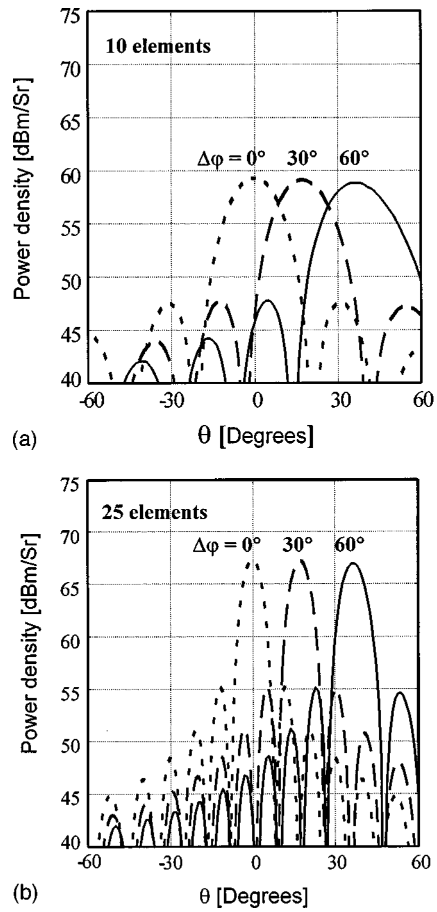

FIG. 3. Radiation pattern for phase differences of 0°, 30°, and 60° between the CRM elements, for 10 (a) and 25 (b) elements.

where A_n and φ_n are the amplitude and phase, respectively, of each CRM-element output. The elements are separated by a distance d in the x direction. In spherical coordinates (r,θ), where $k_x=k\sin(\theta)$, the far-field radiation is given by [10]

$$E_\theta(\theta)=jkZ_0\frac{e^{-jkr}}{2\pi r}F_x. \tag{3}$$

The power density is given by the Poynting vector $|S|=|E\times H|=(1/Z_0)|E_\theta|^2$. The numerical solution dictates how to control $V_{eb}^{(n)}$ and $I_{eb}^{(n)}$ in order to synthesize the desired amplitude and phase difference between the CRM elements.

III. NUMERIC EXAMPLES FOR CRM ANGULAR STEERING

The gain-dispersion relation (1) is solved numerically for the parameters shown in Table I. The complex CRM-element output signals, $A_n\angle\varphi_n$ (see Fig. 1) are used in Eq. (2). Figure 2 shows the CRM output in a contour plot of gain and phase vs electron-beam current and voltage. This graph is useful for the synthesis of the CRM-element operating conditions according to the desired amplitude and phase. Figures 3(a) and 3(b) show examples of radiation lobes in different steering conditions for arrays of ten and 25 CRM elements, respectively. A steering angle of 35° is obtained for a phase shift of 60° between each two adjacent CRM elements in the array. As expected, the 25-element array provides higher gain and directivity than the ten-element array.

IV. DISCUSSION

The CRM-array concept demonstrates a new type of active array antenna for high-power microwaves. The array consists of many low-power CRM elements which share the same magnetic field. These elements combine their total high-power microwave radiation in the far field. An analog electronic control of the electron beams allows a wide radiation steering range (up to $\pm 35°$ continuously).

The proposed concept may lead to a compact device with a relatively small system overhead, and it may alleviate problems of output windows and mode-coupling effects, which characterize high-power gyrotrons. The CRM-array antenna could be used in various applications, including radars, power beaming, plasma heating, and material processing.

Further studies are being conducted in our laboratory in order to elaborate the CRM-array antenna concept. These include theoretical studies of coupling effects among CRM elements and radiating slots, and a construction of an experimental CRM-array antenna.

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