and the ratio of imaginary-to-real frequencies is

$$\frac{\delta_I}{ck\beta} = \frac{\sqrt{3}}{2}\left(\frac{va}{5.76b}\right)^{1/3} \frac{(1 - \eta^2/\beta^2)^{2/3}}{\gamma}. \qquad (18)$$

It can be seen from (16)–(18) that the conclusions reached at the end of Section II are also true in the case of a partially filled guide. Furthermore, in addition to the obvious simplicity of having the beam propagate in a channel, the flexibility afforded by having η available as a design choice is convenient.

IV. Discussion

In addition to the conclusions mentioned at the end of Sections II and III, a few other observations can be made. First, the present system is similar in many respects to beam plasma systems and hence we would expect it to show similar spectral properties [7]. Narrow-band ($\Delta f/f < 0.05$) operation has already been observed at the longer wavelength, and it should as the gain is increased show first multiple mode and then wide-band radiation output. Judicious choice of axial reflections could, as is the case in a beam plasma system, also lead to mode-locked operation.

The present analysis assumes a monoenergetic electron beam. In the case of the relativistic beam, this requirement is less stringent than it is in the nonrelativistic limit. This follows because the velocity spread $\Delta\beta$ is fractionally smaller than the energy spread ($\Delta\beta = \Delta\varepsilon/\beta\gamma^3$). Furthermore, even in the case of a very warm beam the system is unstable and hence it will oscillate. The analysis in the warm limit is conceptually similar but more involved than the one presented above.

Finally, we should mention nonlinear effects and saturation. In the cold beam limit, saturation should occur by beam trapping and, based on experience with traveling-wave tubes and beam plasma systems, we might expect conversion efficiencies in the 10–30-percent range. The efficiency obtained in the long wavelength experiments varies from a few parts in 10^4 up to perhaps one part in 10^3. As further experience with the system is gained, a truly useful radiation source should result.

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Microwave Generation Using Sheet Relativistic Electron Beams

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***Abstract*—Potential advantages in the use of a sheet electron beam for generation of high-power microwave signals are discussed and preliminary experiments to establish their applicability are reported. An examination indicates that sheet beams probably have greatest utility in the frequency, range 10–100 GHz.**

The use of intense relativistic electron beams for the generation of high-power microwave signals has resulted in the development of gigawatt sources at frequencies of less than 10 GHz and megawatt sources at about 100 GHz [1]–[7]. These sources enhance by better than two orders of magnitude [8] the powers available from single source systems. Techniques for the generation of these high-power sources fall into two broad categories; axial bunching devices [1]–[3] such as slow wave systems, and transverse bunching systems such as the cyclotron [4]–[7] maser. The available power from these systems scales approximately as $1/f^{5/2}$ with the wave frequency [8]. At this meeting power levels [9] of about 1 MW at a wavelength of 0.5 mm have been reported and the generation mechanism identified as Raman scattering [10] from fluctuations in the electron beam. Since this generation technique depends on the scattering of a pump wave from an electron beam, the guide dimensions are determined by the beam pump requirements.

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We therefore do not expect that the scattered wave will be subject to the same scaling limitations as indicated above for the various bunching devices. In this instance the interaction efficiency depends on the "quiver" velocity of the electrons in the pump wave fields. To obtain coherent scattering requires threshold pump levels [11] of the order of 50 MW/1 cm^2. The frequency of the scattered wave is related to the pump wave frequency f_p by the relation $f_{sc} \approx 4\gamma^2 f_p$. With an electron beam capability of up to a few megavolts, we require pump waves in the range of tens of gigahertz to generate submillimeter waves.

The generation of millimeter or submillimeter waves therefore requires either the direct generation of the wave or the availability of very powerful sources of radiation in the tens of gigahertz range. We discuss in this article some of the limitations on power production and indicate the possible advantages inherent in the use of striplines for increasing power availability at intermediate frequencies. Initial results of microwave generation experiments using a slow wave system excited by a strip electron beam are also reported.

The scaling of microwave power inversely with the square (or with losses $1/f^{2.5}$) of the frequency arises in conventional tubes from limits set on the electron beam. The E-beam power is, for a thermionic cathode, limited by the current density and hence scales as the area of the guide. This limitation becomes relaxed in the cold cathode devices used for intense E-beam generation. The beam current is determined by the beam-waveguide geometry in the interaction region. For an infinitely thin annular beam of radius a in a drift tube of radius b we find that the space charge limited current is [12], [13]

$$I_{sc} = \frac{8500(\gamma_{inj}^{2/3} - 1)^{3/2}}{\ln(b/a)}.$$

A finite thickness annular beam carries a somewhat smaller current than that given above. Such a beam is also subject to shear and can be liable to diocotron instability. Diocotron instability [14] can be minimized by using a sufficiently strong magnetic field to guide the electron beam. This may result in the limitation of modes which can be excited. Specifically, the negative energy cyclotron wave excitation, in configurations such as the ubitron, would be impossible with magnetic fields large enough to control the diocotron instability in high shear beams. The effects of reducing the beam current below the space charge limit have been analyzed [13] and show that relatively small reductions in the beam current can lead to substantial reductions in the beam shear. Ideally, the beam current does not depend on the size of the drift tube but only on the ratio of the beam-to-waveguide radius. In practice, some limitations arise, principally due to the finite thickness of the beam, which is difficult to reduce below 1–2 mm. Limiting currents of about one-third of the value given above are common in small tubes, whereas one can approach the full limiting current in larger tubes where the beamwidth is small compared to its radius. The beam current can be made large if a thin beam is generated close to the waveguide wall, and for a fixed thickness beam scales linearly with the tube radius. Unfortunately, the beam location is frequently fixed at a given fraction of the tube radius in order that efficient coupling to the wave can occur. For example, in the coupling to a TE_{01} mode it is desirable to have the beam located at about half the tube radius.

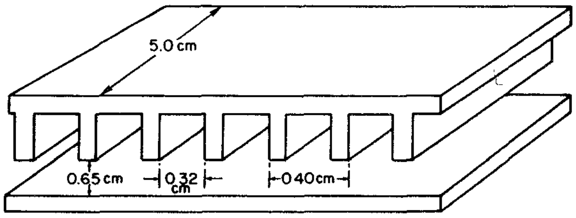

Fig. 1. Schematic of ridged waveguide structure.

It is clear that current density limitations are not the cause of the rapid decrease of RF power with increasing frequency. In addition, the intermediate frequency signals have been mainly generated using the interaction of an harmonic of the cyclotron wave with a higher order TE_{0n} waveguide mode or by the interaction of a "rigid rotor" beam rotating synchronously (or at a rate shifted by the relativistic cyclotron frequency) with the wave fields. The interactions in both cases are rich in harmonic content. Finally, it should be pointed out that the limitations are probably not arising from nonlinear effects except perhaps for the lower voltage (submegavolt) or low frequency (< 10 GHz) regimes. Assuming propagation in the TE_{01} mode at a frequency of about $1.6 f_{c0}$, we find the electric field of the wave is about $3(P)^{1/2}/a$ where P is the wave power and a the tube radius. For a significant nonlinear effect one might expect $\frac{1}{2}E\lambda \simeq (\gamma_d - 1)mc^2/e$ where γ_d is the drift energy of the electrons which is related at the space charge limit to the injection energy by $\gamma_d = \gamma_{inj}^{1/3}$. This only appears likely at powers in excess of 1 GW which have been observed for wave frequencies of less than about 10 GHz, or for submegavolt beams. From a phenomenological point of view, the wave power availability does exhibit a $1/f^{5/2}$ scaling and power is limited below desired levels in both the millimeter and submillimeter regimes.

We now address the issue of using sheet beams for microwave generation and point out some of the differences between the sheet configuration and an annular beam in a waveguide. For a thin beam of width W located between two symmetrically placed conducting boundaries separated by a distance S, the limiting current is

$$I_{sc} = \frac{8500(\gamma^{2/3} - 1)^{3/2} W}{2\pi S}.$$

For a length of beam about one-half of the circumference of the annular beam, one may achieve comparable impedance operation. The factor of 2 ($b - a \simeq s$) arises from the fact that the beam fields extend equally to either waveguide plate. This factor of 2 in the current density may be of significance when bunching is important. More immediately significant, however, is the point that high beam currents

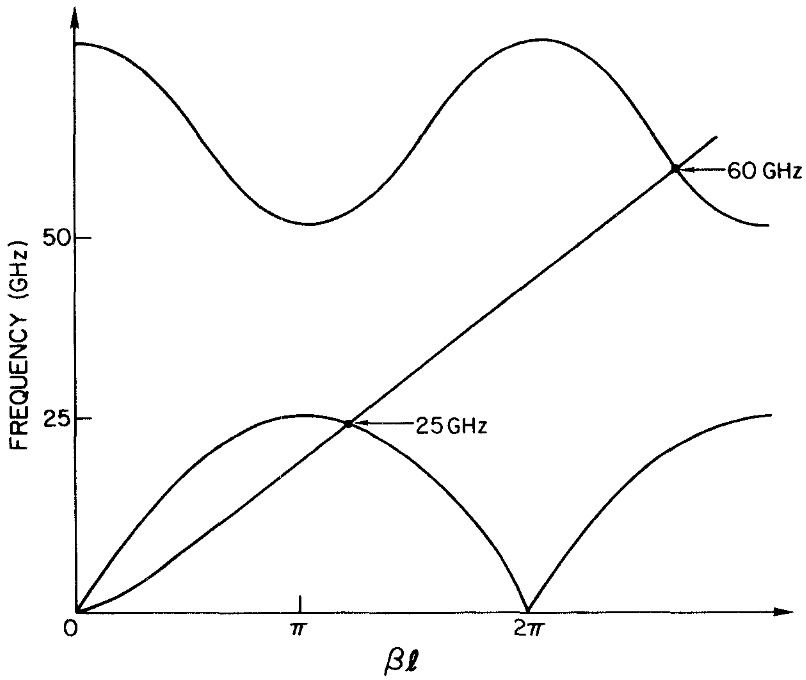

Fig. 2. Brillouin diagram for ridged waveguide structure.

are achieved with the beam located on the axis of symmetry of the system, that is, at the peak axial field location for a TM_{10} mode and the peak transverse field for a TE_{10} mode. It seems possible to produce sheet beams with thicknesses of 1–2 mm and widths of up to 50 cm provided that instabilities can be controlled. The diocotron instability is still expected to be present in this configuration but should be stabilized by a sufficiently intense magnetic field. At comparable beam current densities and with equal microwave power densities, a sheet beam should be capable of enhancing RF power capabilities by one to two orders of magnitude over cylindrical beams, with the greatest effects at the higher frequencies.

Some initial experiments have been carried out to assess the utility of sheet beams for high-power generation. The configuration is shown in Fig. 1 where we illustrate a backward wave oscillator (BWO) designed to operate at about 25 GHz. The BWO configuration was chosen solely for ease of construction and comparison with theory. Other devices such as the cyclotron maser and the ubitron may have better field geometries and permit higher power level operation. The beam was 5 cm wide and had a thickness of about 2 mm. The slow wave structure was formed by a ridge-loaded parallel plate waveguide and had a length of 40 cm. The beam entrance to the structure was tapered to ensure reflection of the backward wave for coupling out of the system. The Brillouin diagram [15] for the structure and a slow space charge wave is shown in Fig. 2. The period and transverse dimensions were chosen for BWO operation. Two systems were used: one with a tooth depth of 2.8 mm and the second with a tooth depth of 1.9 mm. Operation of these two systems should be at frequencies of about 20 and 26 GHz, respectively. The parallel plate structure was mounted in a cylindrical waveguide of 7.5-cm diameter. The tube also provided a return path for the beam current. A gradual taper was used to match the planar guide to the oversize cylindrical system which in turn fed a 10° half-angle cylindrical antenna to couple to free space. The beam was fed from a Marx–Blumlein system at 300–500 keV at a beam current in the range 500–2000 A. This current range was somewhat below the limiting current. The beam was confined and guided by an axial magnetic field of 10 kG. Damage patterns of the beam taken downstream of the structure showed no gross breakup or filamentation at these fields.

The microwave emission was monitored in the *X*, *Ku*, *K*, *Ka*, and *V* bands. With both structures, significant radiation was only monitored in the *K*, *Ka*, and *V* bands. Based on the detector characteristics, we conclude that the deeper tooth structure oscillated at a frequency very close to the cutoff of the *Ka*-band detector and the shallow tooth structure oscillated in the *Ka* band. These results are consistent with calculations of the dispersion relations for the system which predict oscillation at 20–22 GHz and 26–28 GHz, respectively. The *V*-band detector was uncalibrated but recorded RF emission in the 50–75-GHz range. No absolute signal level statements can be made, but the emission was at least 25 dB above the noise level. The *V*-band radiation could arise from an interaction with the second harmonic of the two structures. There was little variation of the output power with the beam voltage or current in the range of conditions used. Varying the length of the structure also enabled us to find the minimum structure length for oscillation. This was about 15 cm for the beam currents used and is in reasonable agreement [16] with calculations of the starting conditions. The excess structure length also enhances the probability of exceeding the switch on conditions for the higher frequency radiation. The complete removal of the structure, or the covering of the ridges with a thin aluminum foil, reduced the signal level by at least 40 dB. Finally, we note that there was no dependence of the radiation, other than that noted above, on the magnetic field strength. The power in both ridged guide structures was estimated to be about 2.5 MW.

The BWO was also operated directly from the Marx and ran at slightly reduced power levels. It was, however, subject to switching on and off during the $\frac{1}{2}$-μs pulse. It seems possible that this results from the poor field geometry, where substantial enhancements of the local electric field can occur close to the sharp corners of the ridges and may result in breakdown. Even allowing operation at only the current power densities, a scaling of the system to a 50-cm width should lead to radiation powers of about 25 MW. This radiation level is comparable to that achieved in the transverse bunching devices. Present experiments are aimed at running with wider beams and at improving the electric field geometry within the slow wave structure. The scaling to greater widths will be accomplished in a coaxial geometry where the inner and outer conductor radii are approximately equal. This has the advantage of removing possible fringing field instabilities and also permits any off-axis waves to grow before decoupling from the system.

We conclude that it seems possible to use striplines as a means of enhancing the total power capability in the intermediate frequency range (say 10–100 GHz). Assessments of overall efficiency and ultimate widths obtainable require additional work. Modest devices appear capable of producing at least comparable power to that achieved using harmonic interactions of the cyclotron maser.

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