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Step-Tunable Far Infrared Radiation by Phase Matched Mixing in Planar-Dielectric Waveguides

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***Abstract*—The mixing of various pairs of CO_2 laser lines in a nonlinear material can produce thousands of step-tunable far infrared (FIR) signals in the range 70-μm–7-mm wavelength with frequency spacings of less than 0.1 cm^{-1}. The major problem in realizing these coherent signals is achieving phase matching in a suitable nonlinear material. In this paper, the interest is in generating tunable signals at the milliwatt level in a planar-dielectric integrated-optics waveguide configuration. Phase matching can be achieved with cubic materials (i.e., GaAs) by adding the waveguide dispersion to the bulk dispersion. Work on the analysis of the waveguide mixing system and its correlation with experimental data are described for a planar GaAs dielectric waveguide in the 100–1000-μm wavelength range.**

I. INTRODUCTION

EVERY scientist and engineer working with coherent radiation appreciates the utility of a tunable narrow spectral line source in evaluating the frequency characteristics of devices and systems, in studying resonances, in high-resolution spectroscopy, as local oscillators in receivers, etc., in any spectral range. This frequency tunable source problem has been particularly difficult in the far infrared (FIR) region where coherent signals of any type only became available [1] in the last ten years.

If one is seeking a tunable source to cover a very broad frequency range, of, for example, 100:1, a beat frequency oscillator would probably be the first choice. The beat frequency between two coherent sources can in principle vary from zero to the sum frequency of the two, yielding an enormous bandwidth. The problem is how to realize this result in practice [2]–[10].

Fortunately, the readily available CO_2 laser with its high power output, its many discrete lines, and high spectral purity exists as a pump source. The problem then resolves into finding the appropriate nonlinear material and achieving phase matching for efficiency.

It is desirable that the material be highly nonlinear and relatively transparent around 10-μm wavelength and in the FIR to avoid attenuation of signals. GaAs is an excellent choice in this respect, but it is a 43-m cubic material not collinearly phase matchable in the bulk form. However, keeping in mind the desirability of integrated optics in the FIR, the GaAs can readily be fabricated into a planar-dielectric waveguide and the waveguide dispersion "added" to the bulk dispersion to achieve phase matching [11], [12].

This dielectric waveguide mixer scheme also has the advantage that Gaussian laser beam divergence encountered in bulk mixing is eliminated, modest power inputs result in large power densities for efficient interaction, and the signal is generated in a TE_0 waveguide mode which has been studied and applied in many devices.

In this paper, two 1–3-kW 0.3-μs-pulsed Q-switched CO_2 orthogonally polarized lasers, having reflection gratings in their optical cavities for line selection, are used to

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excite a TM_0 and TE_0 mode field in a GaAs waveguide. The mixing of these two signals yields a TE_0 mode FIR signal at the milliwatt level.

The waveguide interaction is analyzed, the power formula derived, and the results correlated with experimental data. To date, 20 percent of theoretically calculated power has been realized for signals generated in the 100-μm range of the spectrum.

II. NONLINEAR INTERACTION IN DIELECTRIC WAVEGUIDE

The GaAs waveguide geometry is shown in Fig. 1. For this crystal orientation, the nonlinear polarization associated with TE and TM mode pump fields is

$$P_x^{NL} = -\epsilon_0 d_{14} E_y E_y \quad \text{and} \quad P_y^{NL} = -2\epsilon_0 d_{14} E_x E_y \qquad (1)$$

where d_{14} is the nonlinear coefficient.

The first pump field is a TM mode of the form

$$E_{x1} = A_1 \cos (h_1 x) \exp [i(\omega_1 t - \beta_1 z)] \qquad (2)$$

with the second pump field a TE mode of the form

$$E_{y2} = A_2 \cos (h_2 x) \exp [i(\omega_2 t - \beta_2 z)] \qquad (3)$$

which will produce a FIR TE mode field of the form

$$E_{ys} = A_s(z) \cos (h_s x) \exp [i(\omega_s t - \beta_s z)]. \qquad (4)$$

Outside of the waveguide, the evanescent fields will have the factor $\exp[-p(|x| - d)]$ where $2d$ is the waveguide height.

The characteristic equations for the propagation constants [13] are

$$\beta^2 = \omega^2 \mu\epsilon - h^2 = \omega^2 \mu\epsilon_0 + p^2 \qquad (5)$$

and

$$h \tan (hd - m\pi/2) = \begin{cases} (\epsilon/\epsilon_0) p, & \text{for } TM_m \\ p, & \text{for } TE_m \end{cases} \qquad (6)$$

with m a positive integer.

The equation for the FIR field, driven by the nonlinear polarization is

$$\frac{\partial^2 E_{ys}}{\partial x^2} + \frac{\partial^2 E_{ys}}{\partial z^2} + \omega_s^2 \mu\epsilon_s E_{ys} = -\mu\omega_s^2 P_{ys}^{NL}. \qquad (7)$$

Substituting the appropriate terms from (1)–(4) and neglecting the term $\partial^2 A_s/\partial z^2$, the result is

$$\cos (h_s x) \frac{\partial A_s}{\partial z} = i \frac{\mu\epsilon_0 d_{14} \omega_s^2}{\beta_s} \cos (h_2 x) \cos (h_1 x) A_1 A_2^* \cdot \exp (iz\Delta\beta) \qquad (8)$$

where $\Delta\beta = \beta_s + \beta_2 - \beta_1$.

If (8) is next multiplied by $\cos (h_s x)$ and integrated from $x = -d$ to $x = +d$ and $z = -L/2$ to $z = +L/2$, the value for $A_s(L)$ can be computed to be

$$A_s(L) = \frac{i\mu\epsilon_0 d_{14} \omega_s^2 M}{\beta_s N_s} A_2 A_1^* \frac{L \sin \theta}{\theta} \qquad (9)$$

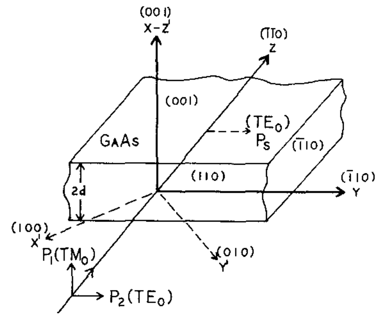

Fig. 1. Waveguide coordinate (x,y,z) system. Crystal coordinate (x',y',z') system. CO_2 laser pumps P_1 and P_2 are polarized in x and y direction to excite a TM_0 and TE_0 mode. FIR signal P_s is generated in a TE_0 mode.

where $2\theta = L\Delta\beta$ and

$$N_s = \int_{-d}^{d} \cos^2 (h_s x)\, dx \qquad (10)$$

$$M = \int_{-d}^{d} \cos (h_s x) \cos (h_2 x) \cos (h_1 x)\, dx. \qquad (11)$$

The average power flow in a waveguide of width y for the pump fields, neglecting depletion, is given by the expressions

$$P_1 = \frac{\beta_1 |A_1|^2 N_1 y}{2\mu\omega_1} \quad \text{and} \quad P_2 = \frac{\omega_2 \epsilon_2 |A_2|^2 N_2 y}{2\beta_2} \qquad (12)$$

where

$$N_1 = \int_{-d}^{d} \cos^2 (h_1 x)\, dx$$

and

$$N_2 = \int_{-d}^{d} \cos^2 (h_2 x)\, dx \qquad (13)$$

while the power in the FIR signal in the waveguide is

$$P_s = \frac{\beta_s}{2\mu\omega_s} |A_s|^2 N_s y. \qquad (14)$$

Substituting for the value of A_s from (9) and using (12), the signal power generated can be expressed as

$$P_s = \left(\frac{\mu}{\epsilon_0}\right)^{1/2} \frac{2 d_{14}^2 \omega_s}{n_{e1} n_{e2} n_{es} c^2} \left(\frac{m^2}{N_1 N_2 N_s y}\right) \left(\frac{L \sin \theta}{\theta}\right)^2 P_1 P_2 \qquad (15)$$

where n_e is the refractive index at the given frequencies.

If the attenuation at frequencies ω_1, ω_2, and ω_3 are included in the derivation, the results can be put in the form

$$\left(\frac{\sin \theta}{\theta}\right)^2 \rightarrow \exp (-\alpha' L) \left(\frac{\sin^2 \theta + \sinh^2 \phi}{\theta^2 + \phi^2}\right) \qquad (16)$$

where $\alpha = 1/2(\alpha_1 + \alpha_2 - \alpha_s)$, $\alpha' = 1/2(\alpha_1 + \alpha_2 + \alpha_s)$, and $\phi = \alpha L/2$.

The signal frequency dependence [14]–[16] of d_{14}, for two pump frequencies greater than the reststrahl frequency ω_0 (37.2 μm), is given by the equation

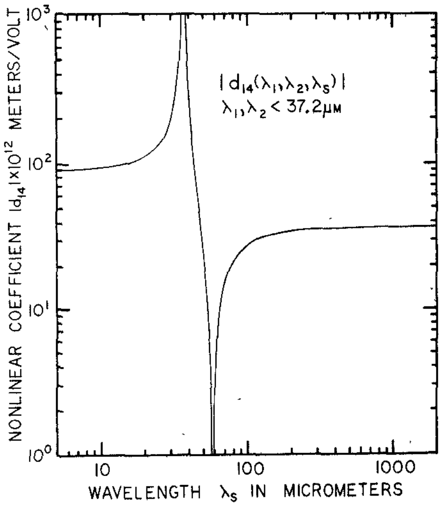

Fig. 2. Nonlinear coefficient $| d_{14}(\lambda_1,\lambda_2,\lambda_s) |$ for $\lambda_1,\lambda_2 > \lambda_{TO}$ (37.2 μm) versus λ_s where $\lambda_s \geq \lambda_1,\lambda_2$.

$$d_{14} = 8.97 \times 10^{-11}\left[1 - 0.59\left(1 - \frac{\omega_s^2}{\omega_0^2} - \frac{i\omega_s\Gamma}{\omega_0^2}\right)^{-1}\right] \text{m/V} \tag{17}$$

where $\Gamma \simeq 0.01\omega_0$ is the linewidth parameter.

A plot of $| d_{14} |$ is given in Fig. 2 where it is seen that for wavelengths longer than 100 μm, $| d_{14} |$ is nearly constant with the value 3.6×10^{-11} m/V.

III. DIELECTRIC GUIDE PHASE MATCHING

Phase matching requires that $\Delta\beta = 0$ or

$$\beta_s = \beta_1 - \beta_2 \quad \text{with} \quad \omega_s = \omega_1 - \omega_2 \tag{18}$$

where β is the waveguide propagation constant in the z direction.

To determine β, one must solve (5) and (6) for a given frequency ω, knowing the bulk dielectric constant $\epsilon(\omega)$.

For GaAs, the dielectric constant ϵ can be represented by the formula [17]

$$\epsilon/\epsilon_0 = 1 + \sum_{i=1}^{2} Se_i\left[1 - \left(\frac{\nu}{\nu_{e_i}}\right)^2\right]^{-1} + S_0\left[1 - \left(\frac{\nu}{\nu_0}\right)^2 + \frac{i\gamma\nu}{\nu_0^2}\right]^{-1} \tag{19}$$

where

$$Se_1 = 4.830 \qquad \nu_{e1} = 23\,000 \text{ cm}^{-1}$$
$$Se_2 = 5.023 \qquad \nu_{e2} = 40\,300$$
$$S_0 = 2.008 \qquad \nu_0 = 269$$
$$\gamma = 5.5 \text{ cm}^{-1}.$$

In Fig. 3 is plotted the refractive index $n = (\epsilon/\epsilon_0)^{1/2}$ for GaAs versus FIR wavelength λ_s. Superimposed in the figure is the waveguide index $n_e = \beta c/\omega$ of several planar-dielectric waveguides made from GaAs, for a TE_0 mode.

As can be seen, the "waveguiding," i.e., reduction of the bulk index, occurs strongly when the waveguide height becomes comparable to the wavelength or smaller. In the near IR, the waveguiding effect of the d = 20-, 40-, and 60-μm waveguide is too small to be displayed on this graph.

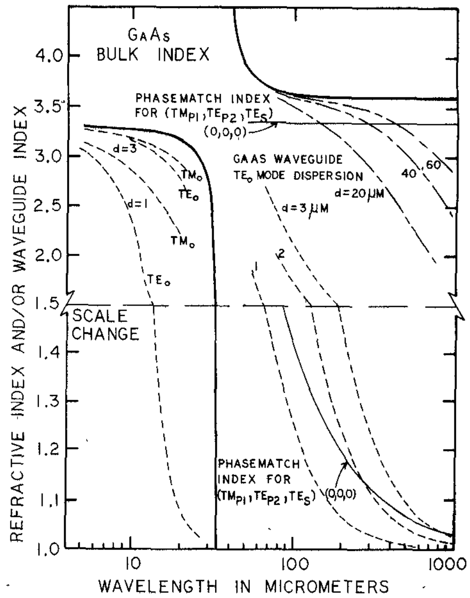

Fig. 3. GaAs bulk index, GaAs waveguide TE_0 mode index for several waveguide thicknesses, and difference frequency mixing phase match index for (TM_{P1},TE_{P2},TE_s) as (0,0,0) mode order versus wavelength.

Also shown in Fig. 3 is the curve of n_e required for phase matching a TM_0 pump, TE_0 pump, and TE_0 generated signal mode set. There are two solutions of d that yield phase matching for each FIR wavelength in this case. The "thin" solution waveguides have a narrower bandwidth due to the large waveguide dispersion at the near IR wavelength.

Only the "thick" solution waveguides will be considered for the remainder of this paper since they represent the most practical broad-band device applications.

In Fig. 4 is displayed, on a somewhat expanded scale: 1) the bulk index for GaAs, 2) the index required for a perfect phase match, and 3) the index obtained with the dielectric waveguide using different pump (TM and TE) and signal (TE) mode orders. Phase matching, for a given waveguide height and pair of pump modes, occurs at a single FIR frequency. If the FIR is step tuned, a phase mismatch will occur and the power generated will follow (15) or (16), being a maximum at the phase match frequency. For frequencies greater or less than the phase match frequency, the power will decrease and limit the useful bandwidth for a waveguide for a given height and length.

The required GaAs waveguide thickness $2d$ versus the TE_0 mode FIR wavelength λ_s, for a TE pump at λ_2 = 10.5912 μm and TM pump, calculated from (5), (6), and (19), for the phase match condition is shown in Fig. 5. Compared to optical integrated dielectric waveguides, the dimensions, as expected, are quite large, which makes fabrication and handling less of a problem.

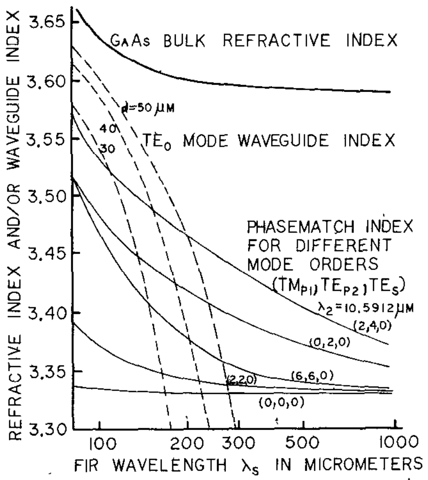

Fig. 4. GaAs bulk index, GaAs waveguide TE_0 mode index for several waveguide thicknesses, and FIR phase match index for several mode order combinations of (TM_{P1},TE_{P2},TE_s) versus FIR wavelength.

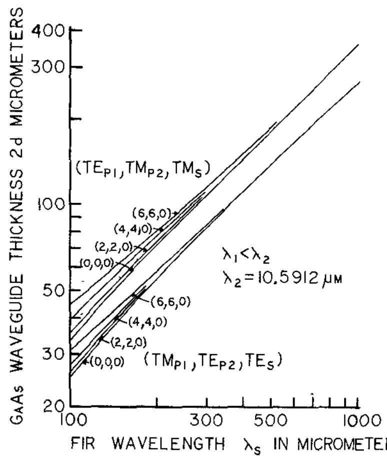

Fig. 5. GaAs waveguide thickness $2d$ to phase match (TM_{P1},TE_{P2},TE_s) or (TE_{P1},TM_{P2},TM_s) for several mode order combinations versus FIR wavelength.

IV. EXPERIMENT

The experimental configuration of the laser is shown in Fig. 6. Each orthogonally polarized CO_2 laser is independently step tuned by means of a reflection grating in its optical cavity. A rotating mirror, common to both cavities, synchronously Q switches the lasers. The pulsed power output of the laser is 1–3 kW on more than 50 lines in the 9.2–10.6-μm wavelength range with a pulse time of 0.30 μs. Typical CO_2 pulse shapes, measured with a Ge photon drag detector, are given in Fig. 7(a) and (b).

The outputs of the two CO_2 lasers are combined into a collinear beam by means of a Ge beamsplitter and focused onto the end face of the GaAs waveguide with a NaCl lens as illustrated in Fig. 8. This straightforward method of coupling the CO_2 radiation into the GaAs waveguide is very effective in exciting a TM_0 and TE_0 mode of the waveguide when the Gaussian laser beam spot radius is made equal to the semiheight d, and the two CO_2 beams do not have to be realigned when their frequencies are changed.

The fabrication of the GaAs waveguide was accomplished by mechanically cutting and polishing a piece of GaAs from a 10^8-Ω·cm boule of material to an optical finish to reduce scattering losses from reflections at the surfaces. The finished waveguide was then placed on a Ge quarter-sphere (25-Ω·cm material), used as an output coupler for the FIR, and mechanically held with a nylon screw. An InSb (4.2-K) detector, with a response time of the order of 0.7 μs, was used to measure the signal.

The responsivity[1] (volts/watt) of an InSb detector varies over nearly four orders of magnitude (1–10 000

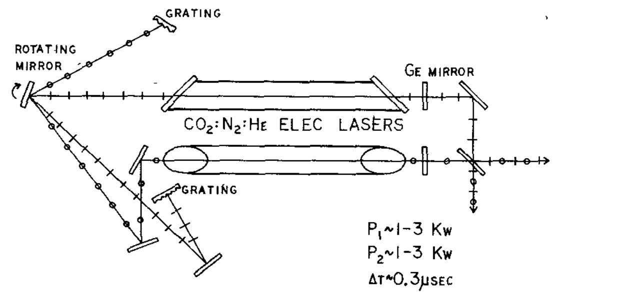

Fig. 6. Experimental laser arrangement showing two independently step-tunable orthogonally polarized synchronously Q-switched CO_2 lasers.

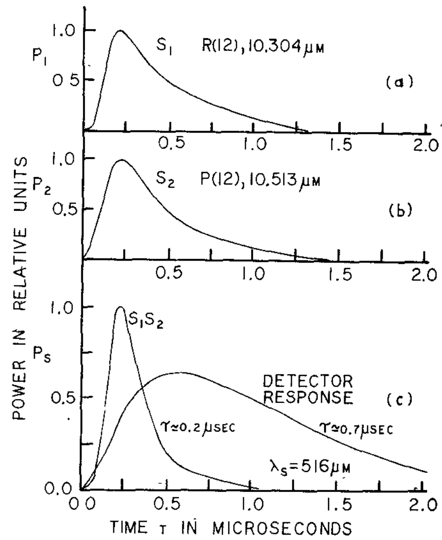

Fig. 7. (a) and (b) show Ge photon drag response to pulsed laser signal at 10.304 and 10.513 μm, respectively. (c) Displays the product signal S_1S_2 from (a) and (b) and the InSb detector response to a 516-μm difference frequency signal.

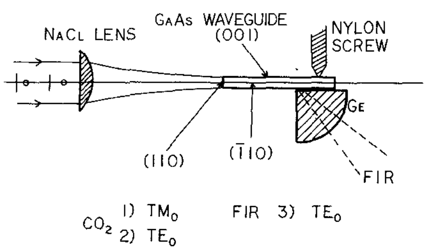

Fig. 8. Dielectric waveguide mixer scheme showing spherical focusing lens, GaAs slab waveguide, and Ge quarter-sphere output coupler.

[1] Raytheon data on long wavelength detector, QKN 1548, n-type InSb at 4.2 K, Raytheon Company, 130 Second Avenue, Waltham, Mass. 02154.

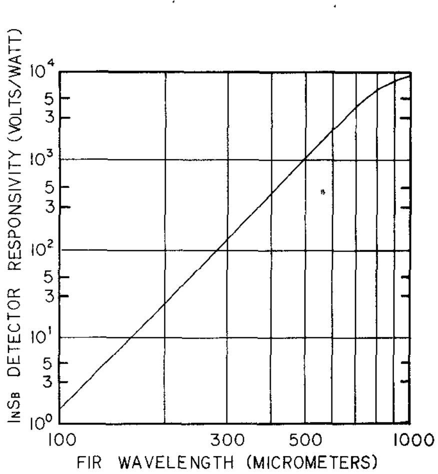

Fig. 9. InSb 4.2-K FIR detector responsivity versus FIR wavelength.

V/W), as seen from Fig. 9, over the 100–1000-μm wavelength range. All the detector data were standardized using this curve. The measurement of pulsed power in the FIR is a difficult problem and represents the greatest source of error in this work.

A typical FIR signal at 516 μm obtained in this work is displayed in Fig. 7(c) along with product signal (S_1S_2) of the two CO_2 lasers. If the CO_2 photon drag detector and the FIR InSb detector were assumed linear with power, and were fast enough to follow their respective signals, then the two curves of Fig. 7(c) should have the same shape. The photon drag detector has a nanosecond response and can obviously follow the 0.3-μs CO_2 pulses, but the InSb detector cannot, which means the output signal never reaches its steady state or peak value.

For example, if one assumes the following model [18] for the detector signal S as

$$\frac{dS}{dt} + \frac{S}{\tau} = I \tag{20}$$

and a step function input I driving function

$$S = \tau I[1 - \exp(-t/\tau)] \tag{21}$$

for $t/\tau \simeq 0.2/0.7$, then $S \simeq 0.25\tau I$.

Using these corrections for the InSb (4.2-K) detector, the data of FIR pulsed power output versus wavelength for two different GaAs waveguides were obtained and plotted in Figs. 10 and 11 along with the theoretical curve (solid line) calculated from (16), normalized to the peak value of the signal. With the exception of the values being only 20 percent of theoretical, the agreement between the experimental and theoretical characteristics is quite satisfactory.

V. CONCLUSIONS

These initial experiments demonstrate that step-tunable FIR pulsed power at the milliwatt level can be generated in an integrated-optics-configuration GaAs-planar-dielectric waveguide pumped with modest power (1–3-kW) CO_2 lasers with an overall efficiency of 20 percent. These signals should have excellent spectral purity (linewidths ~

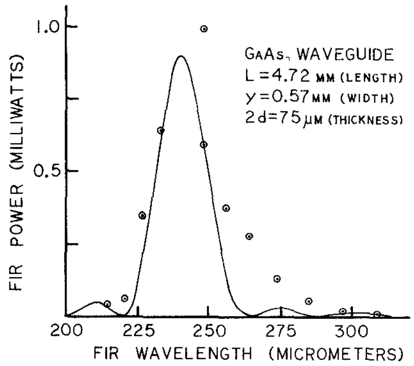

Fig. 10. Theoretical power (×0.2) curve (solid line) and measured FIR power data points versus FIR wavelength for difference mixing in a 4.72-mm × 0.57-mm × 75-μm GaAs waveguide.

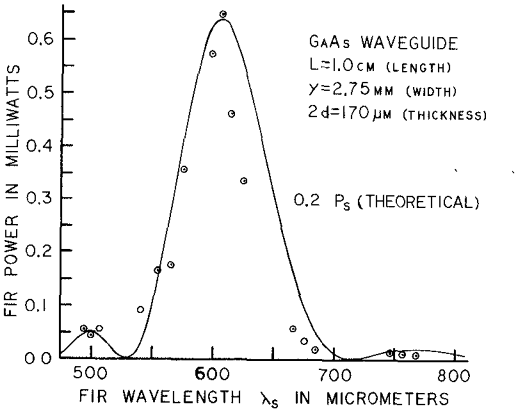

Fig. 11. Theoretical power (×0.2) curve (solid line) and measured FIR power data points versus FIR wavelength for difference mixing in a 1.0-cm × 2.75-mm × 170-μm GaAs waveguide.

10^{-3} cm^{-1}) and be useful in integrated-optics studies, receivers, resonance work, spectroscopy, etc., in this difficult spectral range. When a continously tunable CO_2 or near IR source becomes available, the step-tunable feature of the present experiment can be replaced with a continously tunable FIR signal. In the meantime, step tuning with 0.1-cm^{-1} increments will permit many problems to be explored.

The unclad (air–GaAs–air) planar waveguide used in these experiments was the simplest possible configuration. Various cladded and rib structures could also be used to improve the interaction and bandwidth. Many ideas could be "borrowed" from the area of guided-wave optics for future work in the FIR.

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Strong Submillimeter Radiation from Intense Relativistic Electron Beams

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Abstract—**Radiation from an intense relativistic electron beam at submillimeter wavelengths has been measured with bandpass and high-pass filters. Radiated power ~100 kW has been measured in the passband 390–540 μm. The generation of this radiation depends on giving the electrons a large energy component transverse to the magnetic field. Coherent wave generation mechanisms which may account for the observed radiation are discussed.**

I. INTRODUCTION

DURING the early 1960's rapid advances in high-voltage and pulsed-power technologies led to the development of high-current relativistic electron accelerators [1]–[4]. These accelerators are now capable of generating beam power levels $> 10^{13}$ W for pulse times of 10–100 ns. The unique capabilities of these systems has stimulated intense interest in such diverse areas as material response [5], plasma heating [6],[7], high-energy short-pulse lasers [8], collective ion acceleration [9], and the generation of high-power microwave and submillimeter wave pulses. The present paper is concerned with this latter topic.

A. *Intense Relativistic Electron Beam Technology*

These electron accelerators typically incorporate four major components: an energy storage circuit, a pulse forming network, a low-inductance switch, and a cold-cathode diode. The accelerator employed in the present microwave studies is pictured in Fig. 1. Initially, energy is stored in a Marx generator, a circuit in which the capacitors are charged in parallel but discharged in series. The Marx generator is switched to pulse charge a pulse forming network which in this case takes the form of a coaxial water Blumlein [a folded transmission line with deionized water as the dielectric medium ($\epsilon = 80$)]. The Blumlein is connected in series with a tapered coaxial transformer which increases the voltage at the diode load.

An overvolted water switch terminates the inner coaxial conductor within the Blumlein. When the Blumlein is charged to the desired voltage, the switch closes and a square voltage pulse of 60-ns duration traverses the transformer and is finally applied to the cold-cathode diode [10],[11] which terminates the line. The diode then responds by accelerating an intense electron beam to relativistic energies. This beam propagates along magnetic field lines in an evacuated drift tube where the beam-wave interactions of interest take place.

B. *Microwave Emission from Intense Beams*

Powerful microwave emission from this type of beam was first reported by Nation [12] who loaded the drift tube with a periodic structure. Several research groups [13]–[15] have followed up on this work with periodically loaded drift tubes and a 10-percent efficiency for converting beam energy into microwave energy has recently been reported [15].

Other experimenters have not loaded the drift tube

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