# Tunable Far-Infrared Source-Detector System Based on Landau-Level Transitions in n-InSb

E. GORNIK, W. MÜLLER, AND F. KOHL

*Abstract*—**The radiative emission from impact-ionized shallow donors in n-type InSb provides a tunable far-infrared source, the properties and applications of which are investigated. To obtain optimum conditions, the radiation intensity is studied in dependence of the sample volume and the electric- and magnetic-field intensities. The source is applied to measure the Zeeman splitting of the shallow donors in n-InP and n-GaAs.**

## I. INTRODUCTION

UP TO NOW both Fourier-transform spectroscopy and molecular-gas lasers—having a lot of lines in the submillimeter wavelength range—have been employed as sources of far-infrared radiation to study cyclotron resonance of the free-charge carriers and the Zeeman splitting of shallow donors in a variety of semiconductors. While the operation with the big molecular lasers is complicated, the Fourier-transform spectroscopy sources provide a very low power output and are quite expensive in operation.

Stillman *et al.* [1] were the first to consider the application of recombination radiation from impact-ionized shallow donors as a far-infrared source for detector calibration. In the zero magnetic-field case the strongest intensities measured correspond to electron transitions from the conduction band and excited donor states to the donor ground state [2], [3]. With increasing magnetic field the dominant impurity peak splits, according to the Zeeman effect, into three lines. However, this emission does not provide a suitable far-infrared source, since the magnetic-field-dependent frequency shift is nonlinear and the separation of the individual lines is difficult. On the other hand, the analysis of the magnetic-field-dependent radiative emission from impact-ionized shallow donors in n-type InSb has given evidence of radiative transitions between Landau levels [3] in addition to these impurity transitions.

The energy difference between two Landau levels is linearly proportional to the applied magnetic field and thus provides a new tunable far-infrared source, which can be magnetically tuned from 25 $cm^{-1}$ to 160 $cm^{-1}$ with magnetic fields between 3 kG and 25 kG. According to cyclotron absorption measurements [4], [5], a narrow linewidth of the emission line is expected.

The present work was performed to investigate the properties and applications of this source. In Section II the emission and detection system is described in detail. To obtain optimum conditions, the radiation intensity is studied in Section III in dependence of the sample volume, the electric-, and the magnetic-field intensities. Finally, in Section IV the source is applied to measure the Zeeman splitting of the shallow donors in n-InP and n-GaAs.

Manuscript received May 6, 1974. This work is sponsored by the Fond zur Förderung der Wissenschaftlichen Forschung.

The authors are with the Institut für Physikalische Elektronik der Technische Hochschule, Wien, Austria and the Ludwig Boltzmann-Institut für Festkörperphysik, Wien, Austria.

## II. GENERAL DESCRIPTION OF THE SYSTEM

The major components of the experimental system, which is shown in Fig. 1, may conveniently be grouped as follows:

1) two independent magnetic fields bearing the generation and detector samples, respectively;
2) coupling light pipe;
3) cryogenic system;
4) electrical power and data-conversion system.

The main advantage of this system lies in the fact that two superconducting solenoids are positioned in one and the same helium cryostat. The upper coil (maximum field of 30 kG) bears the n-InSb emitter sample, the other (maximum field of 50 kG) the detector or analyzer sample. A 40-cm-long brass light pipe (10 mm in diameter) conducts the light beam to the detector sample; a sample cone concentrates the radiation. The whole system is immersed in liquid helium. A top-loading helium cryostat gives the possibility for easy sample interchange. The emitter is pulse biased in a duty cycle between $\frac{1}{2}$ and 1/50 and the bias frequency can be varied between 10 Hz and 1 kHz.

The detector output is measured either with a lock-in amplifier or a box-car detector. The power resolution of

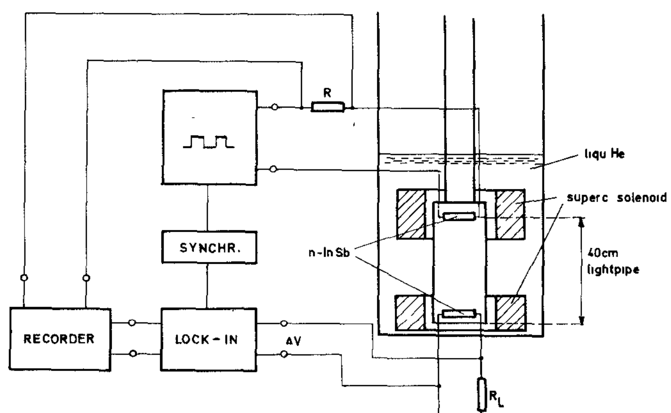


Fig. 1. Schematic diagram of the experimental system.

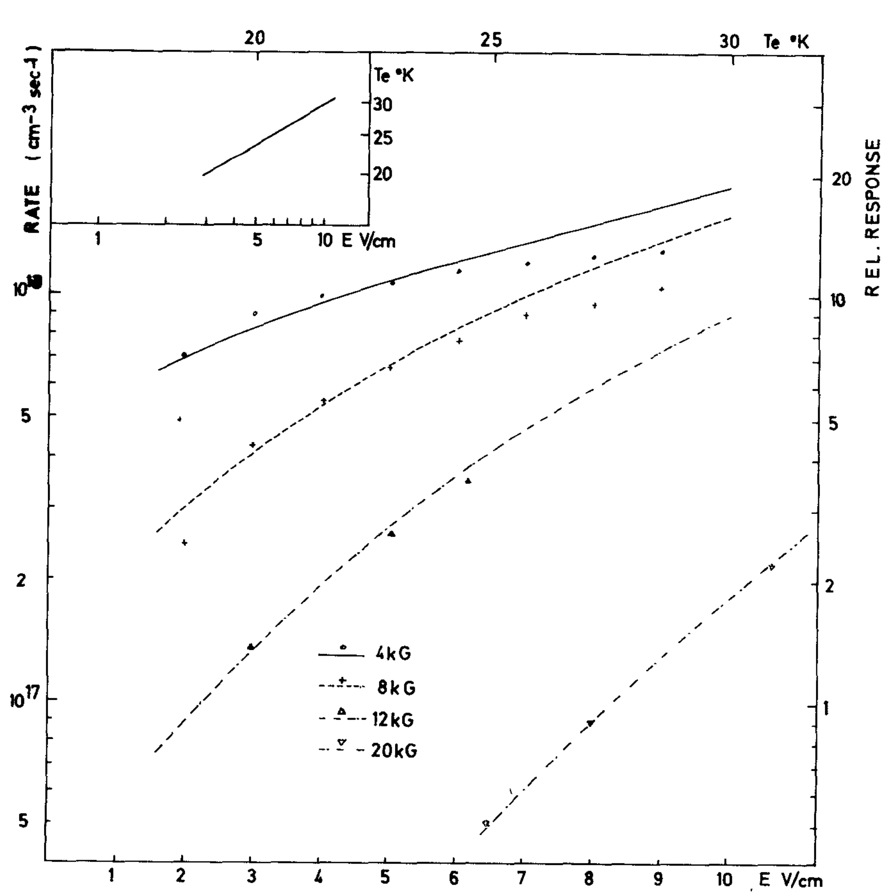


Fig. 2. Dependence of the relative photosignal of the n-InSb-cyclotron resonance detector on the electric field of the emitter for various emitter magnetic fields (experimental points). The full curves show the calculated emission rate in dependence of the electron temperature. The inset shows the electron temperature on electric-field dependence according to [12].

the system is only limited by amplification noise, since the system operates under 4.2-K background conditions. Besides the possibility for photoconductive measurements, as demonstrated in Fig. 1, this system is also suited to perform transmission measurements. In this case, the detector sample can either be mounted in the same magnetic field as the transmitted sample or outside the magnetic field.

The n-InSb emitter and detector samples have a net electron concentration of 4–7 $\times 10^{13}$ cm$^{-3}$, and an electron mobility of 6.4–7.0 $\times 10^{5}$ cm$^2$/V·s at 77 K. Contacts of indium plus 3 percent tellurium are alloyed onto the polished and etched (CP4A) specimen of the typical dimensions 6 $\times$ 4 $\times$ 0.2 mm$^3$.

The Zeeman spectroscopy measurements were performed with epitaxially grown n-GaAs and n-InP samples with a free-carrier concentration and mobility at 77 K of $n = 3 \times 10^{14}$ cm$^{-3}$, $\mu = 7.3 \times 10^{4}$ cm$^2$/V·s and $n = 2 \times 10^{15}$ cm$^{-3}$, $\mu = 4.10^{4}$ cm$^2$/V·s, respectively.

## III. EXPERIMENTAL RESULTS

### *A. Optimization of the Source*

The emitted intensity depends on the occupation number of the higher Landau levels, the radiative transition probability, and the volume of the emitter. The tunable wavelength range and the emission linewidth are determined by the magnetic-field dependence of the dominant nonradiative recombination processes. Additionally, the linewidth is influenced by the nonparabolicity of the conduction band.

The emitted radiation is measured and analyzed with a tunable n-InSb-cyclotron resonance detector, which is used as a far-infrared spectrometer [6]. The measurements are made under breakdown conditions, and hence the population of the higher Landau levels increases with increasing electric field. The dependence of the emitted radiation on the electric field for various emitter magnetic fields is shown in Fig. 2 (experimental points). With increasing electric field there appears a linear magnetic-field dependent increase of the detected photosignal, which shows a saturation tendency at high electric fields; the saturation shifts to higher electric fields with increasing magnetic field. The measurements are compared with calculations of the total emission rate based on an electron-temperature model with the following assumptions: the influence of the impurity states and the nonparabolicity of the Landau levels are neglected, the effective mass is taken to be constant, and $m^* = 0.0139m_0$. Thus we get a total emission rate per volume and second

[7]–[9]

$$R_{\text{tot}} = n \cdot \frac{\eta e^2 \cdot \omega_c^3}{3\pi \hbar c^3 \epsilon_0} l^2 (1 - e^{-\gamma}) \sum_{N=1}^{\infty} N e^{-\gamma N} \qquad (1)$$

with $\gamma = (\hbar\omega_c)/(k_B T_e)$, $T_e$ is the electron temperature, $\omega_c$ is the cyclotron frequency, $n$ is the total free-carrier concentration, $\eta$ is the refractive index, and $l$ is the cyclotron-orbit radius. The sum over $N$ takes into account the contributions of higher Landau levels.

It follows for the total emitted power that

$$P_{\text{tot}} = F \cdot R_{\text{tot}} \cdot \hbar\omega_c \cdot V \qquad (2)$$

when $F$ gives the probability of escape for light for a nondirectional emission and $V$ is the sample volume. According to the method of "refractive index matching," $F$ can be written as [10], [11]

$$F = \left(1 + \frac{\alpha \cdot V}{A \cdot T_{aV}}\right)^{-1} \qquad (3)$$

where $A$ is the emitting surface area, $\alpha$ is the absorption coefficient, and $T_{aV}$ is the average transmission coefficient [11]

$$T_{aV} \simeq \left(\frac{\eta_2}{\eta_1}\right)^2 \cdot \left[1 - \frac{(\eta_1 - \eta_2)^2}{(\eta_1 + \eta_2)^2}\right] \qquad (4)$$

where $\eta_1$ is the refractive index of the semiconductor and $\eta_2$ is that of the ambient.

A comparison of the calculated rate $R_{\text{tot}}$ (in dependence of the electron temperature) with the experimental values is shown in Fig. 2. The agreement is quite reasonable in the electron-temperature range between 20 and 30 K. Deviations from the theoretical behavior begin to occur at high electric fields. The electron temperature on electric-field dependence obtained (as shown in the inset of Fig. 2) agrees with results by Kobayashi and Otsuka [12] from cyclotron-absorption measurement.

Additionally, we used a distribution function of hot electrons in strong magnetic fields computed by Yamada and Kurosawa [13] to calculate the emission rate. As a result, the emission rate saturates at electric fields higher than 10 V/cm, but a too steep increase is predicted for electric fields between 1 and 5 V/cm.

Neglecting self-absorption, one would expect a linear dependence of the emitted power on the sample volume at constant input power per volume. To investigate this important aspect, samples have been prepared with a constant emitting area of 6 × 4 mm² and the thickness varying between 0.15 and 2 mm. The intensity could not be increased by increasing thickness, indicating high absorption losses. Only a very thin sample (70 μm) shows a slight decrease of emission intensity. From this measurement an absorption coefficient of $\alpha \sim 200$ cm$^{-1}$ is found according to (2) and (3).

The extremely high self-absorption and the high refractive index reduce the total emitted intensity very drastically. For a sample with the dimensions 6 × 4 × 0.2 mm³, $F$ has a value of $10^{-2}$, resulting in a total emitted power of about $10^{-8}$ W. An increase of intensity can thus only be performed by increasing the emitting area. Therefore we intend to increase the emitted intensity by a sandwich structure consisting of many thin samples.

To determine the magnetic-field dependence of the intensity and the emission linewidth, we measured the dependence of the photosignal on various emitter magnetic fields for constant emitter current (Fig. 3). For magnetic fields greater than 10 kG, a double structure of the emission line appears due to radiative transitions between Landau levels of both spin configurations. For the lower temperature only, the impurity ground state of the detector is populated. The photosignal consists mainly of the impurity-absorption peak, showing very clearly the spin-split emission line.

The linewidth observed in Fig. 3 is determined both by emitter and detector. To find the spectral width of the emitted radiation, absorption measurements in the same magnetic-field range by Kaplan *et al.* [5] are used under the assumption that the detector linewidth does not change significantly with the temperature between 4.2 and 2 K. The resulting emission linewidth is somewhat broader than the absorption linewidth mainly according to contributions from the higher spin level. At low mag-

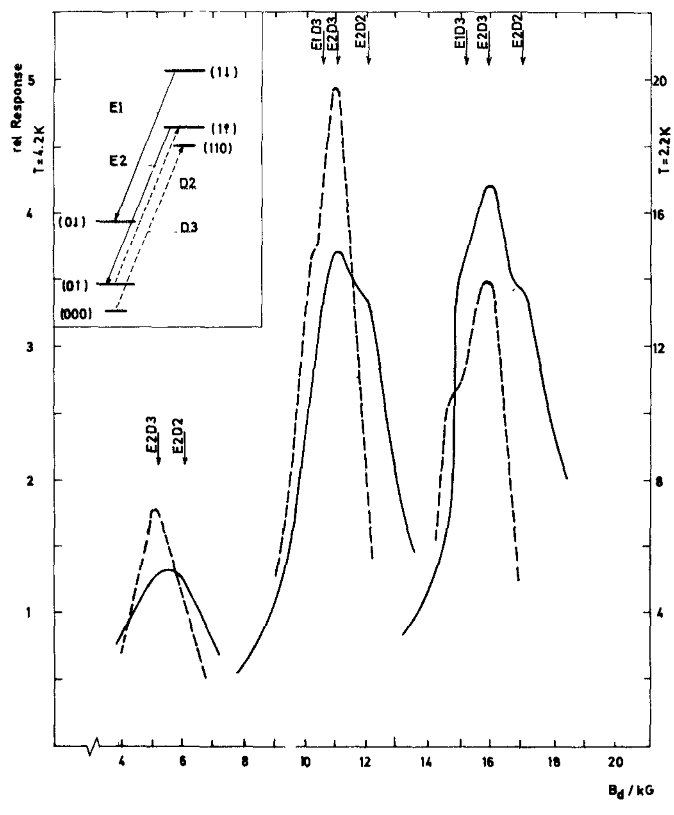


Fig. 3. Magnetic-field dependent photosignal of an n-InSb detector ($B_d$) for various emitter fields (6, 12, and 17 kG) and temperatures of 2.2 K (dashed curves) and 4.2 K (full curves). The inset shows an energy-level diagram for an arbitrary magnetic field. The observed transitions in emission are indicated by arrows in downward direction and the absorption transitions by arrows in upward direction. The emission (*E*) and absorption (*D*) transitions and their respective photoconductive peaks are indicated.

netic fields (6–14 kG) the linewidth is determined to be about 3.5 $cm^{-1}$ and for magnetic fields around 20 kG, the linewidth is about 2.5 $cm^{-1}$. For magnetic fields greater than 25 kG, the photosignal strongly decreases and vanishes at 30 kG.

The best operation is therefore performed at rather low electric fields (only some volts/centimeter); in this case the emission linewidth is not significantly broadened by contributions from the higher spin state and thus is equal to the absorption linewidth.

### B. Application of the Source

As a first application of the source we measured the Zeeman splitting of the shallow donors in n-InP and n-GaAs. Photoconductivity measurements were performed with epitaxially grown samples. Fig. 4 shows the photoconductive signal in dependence of the wavenumber of the radiation, which was determined according to the experimental results of Johnson and Dickey [14], including nonparabolicity. The emitter is biased under constant voltage conditions and therefore the emitter current decreases with increasing magnetic field according to the magnetoresistance of the emitter. The response at zero magnetic field is characterized by a sharp peak for both materials and a shoulder at lower frequencies. The peaks split linearly in the magnetic field and can thus be identified as $1s$–$2p$ transitions belonging to $m = +1$ and $m = -1$.

From the observed splitting, we calculate an effective mass and relative dielectric constant of $m^* = 0.065m_0$ and $\epsilon = 12.5$ for n-GaAs, and $m^* = 0.080m_0$ and $\epsilon = 11.2$ for n-InP, respectively. For n-InP the cyclotron resonance also appears in Fig. 4, from which we determine an effective mass of $0.080m_0$. The preceding results are in good agreement with the literature [15]–[17], giving a good proof for the applicability of the tunable source.

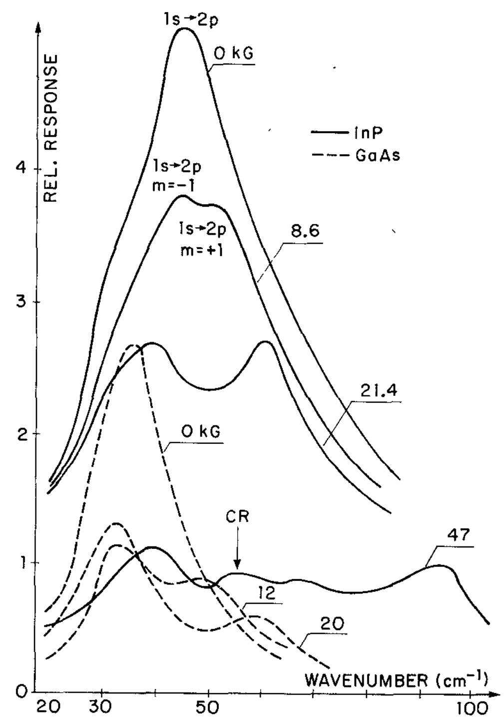


Fig. 4. Photoconductive signal of an n-InP (full curves) and n-GaAs (dashed curves) detector versus the wavenumber of the emitter radiation.

## IV. CONCLUSIONS

We have described a new tunable far-infrared source, which provides a very easily adjustable operation. Because of the low power output of about $10^{-8}$ W and the requirement of liquid-helium temperatures, the n-InSb tunable emitter is best suited if these characteristics do not add further complications. This source is therefore best suited to study the magnetic-field dependence of impurity lines and to determine the effective mass from cyclotron resonance measurements. A problem consists of the separation of the long wavelength radiation—due to electron transitions from the lowest Landau level and excited donor states to the ground state—and the magnetically tunable radiation due to Landau transitions. A separation can be performed with the help of the fact that the two contributions have a different intensity on current dependence [9].

Finally, it should be mentioned that the described system bears the possibility for detector-response time measurements down to nanoseconds because radiation pulses with rise times lower than nanoseconds can be generated.

## ACKNOWLEDGMENT

The authors wish to thank Prof. H. W. Pötzl for his interest in our work and many valuable discussions, H. Phillip for supplying the n-InP, and the Siemens AG Munich for supplying the n-GaAs samples. They also wish to thank Prof. F. Lihl for supplying some experimental equipment and Dr. W. Steiner for technical assistance.

## REFERENCES

[1] G. E. Stillman, C. M. Wolfe, and J. O. Dimmock, "GaAs far infrared detectors and emitters," in *Proc. 3rd Int. Symp. GaAs and Related Compounds* (Institute of Physics, Aachen, Germany, Oct. 1970), Paper Nr. 9, pp. 212–221.
[2] I. Melngailis, G. E. Stillman, J. O. Dimmock, and C. M. Wolfe, "Far-infrared recombination radiation from impact-ionized shallow donors in GaAs," *Phys. Rev. Lett.*, vol. 23, pp. 1111–1114, Nov. 1969.
[3] E. Gornik, "Recombination radiation from impact-ionized shallow donors in n-type InSb," *Phys. Rev. Lett.*, vol. 29, pp. 595–597, Aug. 1972.
[4] J. R. Apel, T. O. Pöhler, T. R. Westgate, and R. I. Joseph, "Study of the shape of cyclotron-resonance lines in InSb using far infrared lasers," *Phys. Rev.*, vol. B4, pp. 436–451, July 1971.
[5] R. Kaplan, B. D. McCombe, and R. J. Wagner, "Cyclotron-resonance line width in InSb in the quantum limit," *Solid State Commun.*, vol. 21, pp. 967–975, Sept. 1973.
[6] M. A. Brown and M. F. Kimmit, "Narrow bandwidth tunable infrared detectors," *Brit. Commun. Elec.*, vol. 10, pp. 609–612, Nov. 1973.
[7] L. C. Robinson, "Physical principles of far-infrared radiation," in *Methods of Experimental Physics*, vol. 10. New York: Academic, 1973.
[8] F. Stern, "Optical properties of semiconductors," in *Solid State Physics*, vol. 15, D. Turnbull, Ed. New York: Academic, 1964.
[9] E. Gornik and W. Müller, "The influence of nonparabolicity on the radiative Landau-emission in n-InSb," to be published.
[10] G. Cheroff, F. Stern, and S. Triebwasser, "Quantum efficiency

of GaAs injection lasers," *Appl. Phys. Lett.*, vol. 2, pp. 173–174, May 1963.
[11] W. Michaelis and M. H. Pilkuhn, "Radiative recombination in silicon p-n junctions," *Phys. Status Solidi*, vol. 36, pp. 311–319, Oct. 1969.
[12] K. L. Kobayashi and E. Otsuka, "Hot electron cyclotron resonance in n-InSb," in *Proc. 11th Int. Conf. Physics of Semiconductors* (Warsaw, Poland), 1972, pp. 903–909.
[13] E. Yamada and T. Kurosawa, "Theory of hot electrons in a strong magnetic field," in *Proc. 9th Int. Conf. Physics of Semiconductors* (Moscow, USSR), 1968, pp. 805–809.
[14] E. J. Johnson and D. M. Dickey, "Infrared cyclotron resonance and related experiments in the conduction band of InSb," *Phys. Rev.*, vol. B1, pp. 2676–2686, Feb. 1970.
[15] R. A. Stradling, L. Eares, R. A. Hoult, and N. Miura, "Zeeman spectroscopy of the shallow donor states in GaAs and InP," in *Proc. Symp. GaAs and Related Compounds* (Boulder, Colo.), 1972, pp. 65–74.
[16] G. E. Stillman, G. M. Wolfe, and J. O. Dimmock, "Magnetospectroscopy of shallow donors in GaAs," *Solid State Commun.*, vol. 7, pp. 921–925, July 1969.
[17] R. Kaplan, M. A. Kinch, and W. C. Scott, "Fourier spectroscopy of shallow donors in GaAs," *Solid State Commun.*, vol. 7, pp. 883–886, July 1969.

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

DAVID E. THOMPSON, STUDENT MEMBER, IEEE, AND PAUL D. COLEMAN, FELLOW, IEEE

***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-$\mu$m–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-$\mu$m 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-$\mu$m 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-$\mu$s-pulsed $Q$-switched $CO_2$ orthogonally polarized lasers, having reflection gratings in their optical cavities for line selection, are used to

Manuscript received May 21, 1974. This work was supported by the Air Force Office of Scientific Research under Contract 71-1981 and by the Industrial Affiliates Program on Physical Electronics of the College of Engineering, University of Illinois.

The authors are with the Electro-Physics Laboratory, Department of Electrical Engineering, University of Illinois, Urbana, Ill. 61801.