the photopeak disappears.

To attain improved resolution with CdTe, it will be necessary to increase the mobility and trapping time products, especially for holes. At lower photon energies such an increase would not only reduce trapping, but would also allow lower biases to be applied and consequently reduce thermal noise. The resolution at higher photon energies appears to be limited by the escape of the photoelectron. Therefore, increasing device size should result in a significant improvement.

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[1] K. Zanio, J. Neeland, and H. Montano, IEEE Trans. Nucl. Sci. NS-17, 287 (1970).
[2] *Proceedings of the International Symposium on Cadmium Telluride, a Material for Gamma-Ray Detectors*, edited by B. Siffert and A. Cornet (Centre de Recherches Nuclearies, Strasbourg, France, 1971).
[3] J.M. Palms, in *Semiconductor Detectors in the Future of Nuclear Medicine*, edited by P. Hoffer, R. Beck, and A. Gottschalk (Nuclear Medicine, New York 1971), Chap. 5.
[4] M. Martini, H. Montano, and K. Zanio, Nucl. Instr. Methods (to be published).
[5] N. Kyle, J. Electrochem. Soc. 118, 1790 (1971).
[6] W. Akutagawa and K. Zanio, J. Crystal Growth 11, 191 (1971).
[7] J.H. Hubbell, National Standard Reference Data System, National Bureau of Standards Publication No. 29 (U.S. GPO, Washington, D.C., 1969).
[8] W.F. Titus, Phys. Rev. 115, 351 (1959).
[9] W. Akutagawa and K. Zanio (unpublished).

Four-Hundredth-Order Harmonic Mixing of Microwave and Infrared Laser Radiation Using a Josephson Junction and a Maser

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For mixing in a Josephson junction at infrared frequencies, we have shown that the available power from the junction increases as the intermediate frequency is increased. Following this result an infrared receiver has been developed incorporating a 9-GHz maser preamplifier at the i.f. Using this system, the beat between the 401st harmonic of a high-quality microwave source and a 3.8-THz infrared laser has been observed. Also, for low-order mixing at 3.8 THz, a comparison of beat signals from a Josephson junction and a room-temperature mixer has been made.

Our first experiments on infrared frequency synthesis using Josephson junctions[1] involved mixing between the approximately 100th harmonic of an X-band microwave source and the HCN laser at 0.891 THz with a beat frequency output at 60 MHz. As a significant step in the direction of higher frequencies we have improved the earlier system and can now produce a 46-dB signal-to-noise ratio for a beat from the 3.8-THz (78-μ) emission of the water-vapor laser. The 3.8-THz radiation is only a factor of 7 lower in frequency than the highest cw frequency[2] that has been measured relative to microwave frequencies.

The first step in improving the Josephson-junction system was to study the dependence of the output signal level on the output frequency (i.e., the i.f.) It was first pointed out by Josephson[3] that these junctions behave as parametric inductances, and from the general arguments of Manley and Rowe[4] for parametric devices it is well known that in an ideal parametric down-converter the available power from the mixer follows the relation

$$\frac{P_{\mathrm{i.f.}}}{P_s} = \frac{\nu_{\mathrm{i.f.}}}{\nu_s} \qquad (1)$$

if negative resistance effects are excluded. The left-hand side is the ratio of i.f. and input signal powers and the right-hand side is the ratio of their respective frequencies. The exact dependence that is observed in a practical case, however, depends on the circuitry attached to the parametric element.[5] For the experiments described here we have concerned ourselves with impedance matching only at the i.f. and at the highest incoming infrared laser frequency[6]; we have ignored such questions at the remaining multitude of frequencies present in the junction.

We have studied the dependence of the junction output at the i.f. for applied signals both in the microwave range and in the infrared and obtained essentially the same results.[7] Infrared measurements at 3.8 THz will be emphasized here. The basic experiment involves mixing between the fourth harmonic of the 0.964313-THz (311-μ) line from the HCN laser and the fundamental 3.821774-THz (78-μ) line[8] of the water-vapor laser giving a beat at 35.479 GHz. By applying an additional frequency to the same junction, the 35-GHz beat can be down-coverted to our receivers' frequencies. The three different receiver front ends that were used are char-

TABLE I. Summary of mixing experiments at 3.8 THz (78 μ).

Experiment No. and synthesis scheme[a]	Mixer	Receiver front end	Receiver input noise temp.[b] (K)	Observed signal-to-noise ratio[c] (dB)	Receiver noise bandwidth[d] (kHz)	Signal power at receiver input[e] ($\times 10^{-14}$ W)	Available signal power at junction[f] ($\times 10^{-14}$ W)
I $4\nu_{311}-\nu_{78}$ -4×8.86515 GHz	Josephson junction Nb-Nb point contact at 2 K	Conventional 18-MHz amplifier	850	7	8	0.047	0.188
II $4\nu_{311}-\nu_{78}$ -3×8.89815 GHz		Conventional 8.8-GHz balanced mixer	2000	18		1.39	13.9
III $4\nu_{311}-\nu_{78}$ -5×8.89580 GHz		9.0-GHz traveling-wave maser	75	35		2.62	26.2
IV $4\nu_{311}-\nu_{78}$ -26.479 GHz		9.0-GHz traveling-wave maser	75	46		33.0	330
V ν_{78} -401×9.50817 GHz		9.0-GHz traveling-wave maser	75	17		0.041	0.41
VI $4\nu_{311}-\nu_{78}$ -35.457 GHz	W-Ni point contact at room temp.	Conventional 22-MHz amplifier	650	40	10	89.0	178

[a] The frequencies of the beat signals are the tabulated algebraic sums. The origin of a signal on the spectrum analyzer is confirmed by shifting the frequency of each of the applied oscillators in turn and noting whether the corresponding frequency shift of the beat signal is in the ratio of the harmonic number of the desired process.

[b] The tabulated noise temperatures for the three conventional amplifiers represent noise generated in the amplifiers or mixer diodes but referred to the input. For the maser the the observed noise is not generated in the amplifier (noise temp. ≈2 K) but originates in thermal sources in the attached microwave circuitry, part of which is at room temperature. No change in noise is observed between having the applied signals on or off the junction.

[c] The signal-to-noise ratios are determined from spectra such as Fig. 1. The rms noise level is estimated from the "grass" on either side of the spectral line and this is then compared with the height of the line.

[d] These entries are the 3-dB widths for the resolution bandwidth (predetection bandwidth) of the spectrum analyzer. The postdetection bandwidth of the analyzer is large compared with the resolution bandwidth.

[e] These results approximate the total signal power of the spectral line. They are obtained by estimating the total noise power within the 3-dB width of the spectral line and then multiplying by the power ratio determined from the signal-to-noise-ratio column.

[f] For experiments I and VI the signal power at the junction is obtained from the preceding column simply by multiplying by the appropriate impedance mismatch factor obtained by assuming that the junction impedance at the i.f. is equal to its dc resistance at the operating bias point. (Changes in amplifier noise temperature due to input impedance mismatching are negligible.) For the microwave i.f. the procedure was different since the junction is mounted in a cavity resonant at the i.f. and resistive losses in the circuitry are significant. The junction is mounted in reduced height waveguide (1.5 mm high) with a sliding short behind the junction forming one end of the cavity and a sliding stub tuner outside the Dewar forming the receiver end of the cavity. With this arrangement the cavity resonances were 114 MHz apart and the cavity could be simultaneously matched on two adjacent resonances, e.g., one at 8.800 GHz and the other at 8.914 GHz. Local oscillator power at 17.714 GHz was then directed on the junction, and the applied signal level at 8.914 GHz required to produce a given receiver response at 8.800 GHz was measured. The receiver response was subsequently calibrated. Using this method we found that the conversion loss of the system was 14 dB with high-impedance junctions (≈ 60 Ω) and 20 dB with low-impedance junctions (≈ 10 Ω). For our infrared mixing experiments, low-impedance junctions are used. We hypothesize that 10 dB of the 20-dB loss occurs by signal dissipation and impedance mismatch going into the junction at 8.914 GHz and the other half or 10-dB loss for the signal coming out at 8.800 GHz. Hence we use 10 dB as the loss factor to obtain the last column from the preceding column for experiments II–V.

acterized in Table I. The visual output of the system was the usual oscilloscope display of a spectrum analyzer. One of the better signals obtained with the maser is illustrated in Fig. 1. From photographs of this type, the signal-to-noise ratio for a given experiment can be determined, and the *best results* for each case are tabulated in Table I. For all of the listed experiments the power at ν_{78} should be assumed the same, and all other signal levels are adjusted to give the maximum signal. The main result in the table is the last column listing the available signal powers in the junctions for the various experiments. Comparisons of these numbers give the relative efficiencies of the different experiments for producing a beat signal from the 3.8-THz laser.

From experiments I to II of the table, the intermediate frequency ($\nu_{i.f.}$) is changed by a factor of 489 and results in a change in the available signal power by a factor of 74. This is clear evidence for parametric action in the mixer[9] and is surprisingly close to the linear $\nu_{i.f.}$ dependence of Eq. (1). Although day-to-day variations of the laser output power, focusing conditions, and optimum junction adjustment introduce uncertainties of approximately ± 3 dB for the signal power in experiments III–V, no such uncertainties are involved for I

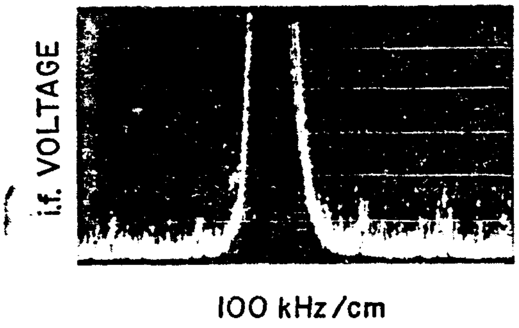

FIG. 1. Typical spectral display of a beat signal. It represents data of experiment III of Table I with sufficient gain for measurement of the noise level adjacent to the spectral line. The line peak is off scale but has an equivalent height of 34 cm. The scope display is 6×10 cm.

and II. These experiments were done within minutes of each other without changing the above parameters and were reproducible within 25%.

Experiments III—V are all at the same i.f. but involve substantial differences in harmonic numbers. To discuss these results we focus on the number of sidebands N which are produced from the primary spectral line. The logic here is to consider ν_{78} as the signal to be detected and then to determine over how many sidebands the fundamental power in ν_{78} is distributed by the mixing process. For example, multiplication of ν_{311} by 4 and mixing with ν_{78} takes power from the primary line and puts it into sidebands at $\nu_{78} \pm l\nu_{311}$, where $l = 1, \ldots, 4$, resulting in eight sidebands.[10] If, as in experiment III, the fifth harmonic of another signal is also added, $N = (2\times5)\times(2\times4) = 80$. In Fig. 2 the results of experiments III—V are summarized, and it is ascertained that within experimental error the maximum beat signal power is proportional to N^{-2}. Note that if all fundamental power went only into N sidebands, then the result would be N^{-1}. The N^{-2} empirical rule is useful for designing frequency-synthesis experiments.

Experiment V is unique in that ν_{78} was detected by beating it directly with the 401st harmonic of a klystron, i.e., without a lower-frequency laser. For the purpose of very accurate frequency synthesis, the use of a single reference oscillator is much to be preferred if the signal-to-noise ratio is adequate. Substantial effort was required to develop a microwave source with the requisite spectral purity for this experiment. The final arrangement consists of a primary reflex klystron stabilized by a resonant cavity and, in addition, injection locked by a secondary klystron which is electronically phase locked to a quartz oscillator. In this mode of operation the good long-term stability of a quartz oscillator is transferred to the primary microwave source without introducing substantial high-frequency noise.[11]

Not every Josephson-junction adjustment gives the result of experiment V; in fact, with the present instrumentation it appears that a necessary requirement for seeing the beat is observation of the 3.8-THz current step[1,12] at 7.9 mV on the dc current-voltage curve. The step is not required for lower-order harmonic mixing as in III and IV, presumably because the beat signal-to-noise ratio is so much better.

Since most infrared-frequency measurements have been made with room-temperature W-Ni point contacts,[3] we did experiment VI of Table I to compare their operation with a Josephson junction as in IV, where the harmonic order of the mixing is the same. We found that for low-order harmonic mixing the available power from the W-Ni device is comparable (≈ 3 dB less) to that from the Josephson junction, but presumably the intrinsic noise in the Josephson device is much less; hence, much better signal-to-noise ratios can be obtained in the future. It is difficult to compare the intrinsic sensitivities of the basic physical mechanisms involved in the two devices since the W-Ni device uses a much smaller diameter whisker (5 μ compared with 125 μ) which may give better (or worse) antenna coupling properties,[6] and because the shunt capacitance of the W-Ni device is much less than for the Nb-Nb contact. The estimated contact areas are 0.04×10^{-8} cm^2 for W-Ni [13] and 25×10^{-8} cm^2 for the Josephson device.

In any case the Josephson junction remains unequalled in its ability to generate high-order harmonics of a microwave source. Improvements in impedance matching and junction capacitance could improve our signal-to-noise ratios by 20 dB or more.

It is a pleasure to acknowledge the assistance of Nolan Frederick in this work and useful discussions with David Wait and Donald Halford. We also want to thank Gerald Arthur for the loan of the maser and Ray Stepuro of Sperry Rand Corp. for the loan of essential microwave equipment.

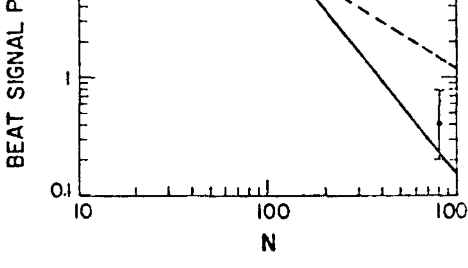

FIG. 2. Dependence of available beat signal power on the number of sidebands N. The data are from experiments III—V of Table I. Uncertainties of ± 3 dB have been assigned to each data point for reasons explained in the text.

McDonald, A.S. Risley, J.D. Cupp, and K.M. Evenson, Appl. Phys. Letters 18, 162 (1971).

M. Evenson, J.S. Wells, and L.M. Matarrese, Appl. Phys. Letters 16, 251 (1970).

D. Josephson, Rev. Mod. Phys. 36, 216 (1964).

M. Manley and H.E. Rowe, Proc. IRE 44, 904 (1956).

E. Zimmerman and N.V. Frederick, Appl. Phys. Letters 19, 16 (1971). In this work it was shown that the output power of a Josephson junction in a SQUID configuration could be increased by a factor of 10 if the bias frequency were increased by the same factor. Our work is with a current-biased device and spans a much greater range of intermediate frequencies but not with such ideal behavior.

M. Matarrese and K.M. Evenson, Appl. Phys. Letters 17, [illegible] (1970).

It should be noted in what follows in the text that the basic experiment is down-converting a fixed frequency signal at 35 GHz, i.e., the infrared frequencies are not changed at all. Consequently, one might expect the same results in the infrared experiments as with an applied signal at 35 GHz. However, to produce a 35-GHz signal from two infrared sources, substantially more power must be applied to the junction than in the microwave case (see the theory of Ref. 1), and therefore junction performance is expected to be different (indeed, the Josephson effect can be suppressed with sufficient applied power).

[8] We did two calibrations of this frequency and obtained 3.8217733 and 3.8217755 THz ± 3.0 MHz (uncertainty in setting the laser on the peak of its gain curve), both in excellent agreement with K.M. Evenson, J.S. Wells, L.M. Matarrese, and L.B. Elwell [Appl. Phys. Letters 16, 159 (1970)].

[9] For the usual resistive or diode mixer, the available output power tends to be independent of the intermediate frequency.

[10] Obviously the actual physical processes are far more complicated than this simple sideband counting scheme suggests.

[11] A description of this system will be submitted for publication by J. Robert Ashley, A.S. Risley, and Frank M. Palka [IEEE Trans. Microwave Theory Tech. (to be published)].

[12] The largest step we have produced at 3.8 THz is ≈ 5 μA in a junction with a critical current of 150 μA and a normal state resistance of 10 Ω. Since the step and beat amplitudes increase with power up to the maximum 3.8-THz power that is available (≈ 5 mW), larger beat signals could be obtained if more laser power were available. It was possible to suppress the supercurrent only by a factor of 2 in the junctions normally used, i.e., for critical currents $\gtrsim$ 150 μA.

[13] R.L. Abrams and W.B. Gandrud, Appl. Phys. Letters 17, 150 (1970); D.R. Sokoloff, A. Sanchez, R.M. Osgood, and A. Javan, *ibid.* 17, 257 (1970).

Nonresonant Energy Transfer from Er^{3+} to Yb^{3+} in LaF_3

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Energy transfer in LaF_3; Er, Yb is studied by observing the lifetimes of Er^{3+} in excited states and the excitation spectra both at room temperature and at 77 °K. It is found that the energy transfer from Er^{3+} ($^4S_{3/2} \to {}^4I_{13/2}$) to Yb^{3+} ($^2F_{7/2} \to {}^2F_{5/2}$) is associated with the emission of three phonons of about 350 cm^{-1}, and that the energy transfer from Er^{3+} ($^2H_{9/2} \to {}^4F_{9/2}$) to Yb^{3+} accompanied by the absorption of phonons takes place.

Recently, Miyakawa and Dexter[1] proposed a theory for the nonresonant energy transfer associated with phonons. According to the theory, the probability of the energy transfer is given by

$$W = W_0 \exp(-\beta \Delta E), \tag{1}$$

where ΔE is the energy mismatch (the difference between the transition energies of a donor and an acceptor), β is a constant which depends on the nature of phonons of a host lattice and the strength of electron-phonon coupling, and W_0 is the probability if ΔE is equal to zero.

The probability also depends on the number of excited phonons, and at temperature T it is expressed, analogously to a multiphonon relaxation process,[2] as follows:

$$W(T) = W(\bar{n}_i + 1)^N, \tag{2}$$

for the energy transfer involving the emission of N phonons, and

$$W(T) = W(\bar{n}_i)^N, \tag{3}$$

for the absorption of N phonons, where $\bar{n}_i$ is the average occupation number of the ith vibrational mode and is given as

$$\bar{n}_i = [\exp(h\nu_i/kT) - 1]^{-1}. \tag{4}$$

The exponential dependence on ΔE in Eq. (1) was observed in Y_2O_3.[3] The temperature dependence of the energy-transfer probability in Y_2O_3; Eu^{3+},Yb^{3+} was observed to be in agreement with Eq. (2), and implies that the energy transfer concerned is associated with the emission of phonons.[4]

We have investigated the energy transfer from Er^{3+} to Yb^{3+} in LaF_3, which is one of the popular infrared-to-visible converting phosphors. We observed various kinds of energy transfers from Er^{3+} to Yb^{3+} and found that they are associated with the emission or the absorption of phonons.

Figure 1 shows the relaxation rate of the $^4S_{3/2}$ state and that of the $^2H_{9/2}$ state of Er^{3+}, both at room temperature and at 77 °K, as a function of Yb concentration. The former increases with Yb concentration both at room temperature and at 77 °K. This is due to the energy transfer from Er^{3+} ($^4S_{3/2} \to {}^4I_{13/2}$) to Yb^{3+} ($^2F_{7/2} \to {}^2F_{5/2}$).[5] The latter also increases with Yb concentration at room temperature, whereas it is almost independent of Yb concentration at 77 °K. This fact indicates that the energy transfer from Er^{3+} ($^2H_{9/2}$) to Yb^{3+} takes place at