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HETERODYNE LASER RADIATION DETECTION AT 891 GHz USING JOSEPHSON POINT CONTACTS (*)

T. G. BLANEY

Division of Electrical Science, National Physical Laboratory, Teddington, Middlesex, England

Résumé. — Pour étudier les performances d'un détecteur hétérodyne à 891 GHz on a utilisé un laser continu HCN comme oscillateur local, et une jonction Josephson à contact à pointe Nb-Nb, comme mélangeur. On a pu réaliser des fréquences intermédiaires (IF) jusqu'à quelques MHz, en utilisant un autre laser HCN comme générateur de signal. On a employé à la fois des jonctions pré-réglées, et des jonctions ajustables. Ces dernières donnant la meilleure sensibilité car elles permettent de focaliser le rayonnement directement sur la jonction. On étudie l'influence du courant continu de polarisation, et de la puissance de l'oscillateur local sur la puissance IF. Celle-ci varie linéairement avec la puissance du signal pour des niveaux inférieurs à 10^{-5} ou 10^{-6} W. Le rendement de conversion du mélangeur est indépendant de la fréquence intermédiaire. La sensibilité du détecteur dépend fortement des caractéristiques et s'étend sur plusieurs ordres de grandeurs pour les jonctions étudiées. Le bruit est essentiellement celui du préamplificateur à température ambiante avec une température de bruit de l'ordre de 500 K. Les pertes par conversion minimales sont de l'ordre de 29 dB. Elles incluent les pertes dues à la désadaptation à l'entrée. La meilleure sensibilité obtenue pour le système de réception est de 10^{-17} W/Hz.

Abstract. — Experiments were carried out to investigate the performance of a heterodyne detector at 891 GHz using a cw hydrogen cyanide laser as the local oscillator and Nb-Nb point contact Josephson junctions as mixing devices. Using a second off-tuned HCN laser as the signal, intermediate frequencies (IF's) up to a few MHz could be studied. Both pre-set and adjustable types of junction were used, and the latter, arranged so that radiation could be directly focussed onto them gave the best ultimate sensitivity. Dependence of the IF power on dc current bias and local oscillator power is described, and compared with simple theory. IF power varied linearly with signal power for signals less than 10^{-5} to 10^{-6} W. The mixer conversion efficiency was independent of IF. The sensitivity of the detector was a strong function of junction characteristics and ranged over several orders of magnitude in the junctions studied. Noise at the output was dominated by the room temperature preamplifier with a noise temperature of about 500 K. The smallest observed value for conversion loss of the junction was about 29 dB. This figure includes the signal input matching loss. The best sensitivity of the whole receiving system was equivalent to 1×10^{-17} W/Hz.

1. Introduction. — The Josephson point contact mixer could form the basis of a useful heterodyne detector in the submillimetre region when used with an external local oscillator. The potential merits of such a detector, which include high intermediate frequency (IF) bandwidth and low intrinsic noise can only be utilised if the signal power can be matched into the junction reasonably well, and if the conversion efficiency (from signal to IF power) is not too low.

In this paper, experiments will be described in which two lasers operating near 891 GHz provided the signal and local oscillator (LO) frequencies. Mixing was carried out with Nb-Nb point contacts to give IF's up to a few MHz. The results give some indication of the combined conversion and signal input matching loss which can be achieved with quite simple apparatus, and of the minimum detectable power of a complete detector system using a room temperature IF preamplifier.

2. Theory. — At present, there is no simple and adequately precise analytical model for mixing behaviour in Josephson weak link devices. Several theoretical treatments exist in the literature (for example [1], [2], [3], [4]).

In the present work, the IF was much smaller than the signal frequency. In this regime, a relatively simple but inexact theory [1], [5], which assumes the junction is driven from constant-voltage sources, can be tried. This theory is qualitatively useful, but its quantitative predictions are largely unverified. As will be seen from the experimental results, a dc current bias is required for operation of the mixer, and the most efficient mixing is usually obtained with the bias set to a current just exceeding the amplitude of the zero voltage supercurrent (the latter is a function of LO power). Using formulae in [5], a simple expression for conversion efficiency, E , at this bias point can be obtained

$$E = \frac{\text{IF power}}{\text{Signal power}} = \frac{1}{4} \left(\frac{2e}{hf} \right)^2 I_0^2 R_d R_s F(P_L) \quad (1)$$

(*) Work carried out under a contract with the Culham Laboratory of the UKAEA.

where R_d is the junction differential resistance at the bias point, R_s is the junction resistance presented to the signal (reactive components of the junction impedance are neglected), f is the signal frequency, I_0 is the junction critical current (with no incident radiation) and

$$F(P_L) = \left[J_1 \left(\frac{2 e P_L^{1/2} R_s^{1/2}}{h f} \right) \right]^2$$

where J_1 is a Bessel function of the first kind and P_L is the LO power. Perfect output matching of the IF signal is assumed. Formula (1) agrees with the expression (15) in [2] when an appropriate substitution for $\left(\frac{\partial I_0}{\partial I_{RF}} \right)$ in the latter expression is made. There is a grand maximum value for $F(P_L)$ (about 0.35) and thus, for a given junction and signal frequency, an optimum value of P_L . P_L is optimum when adjusted to produce the first maximum in the width of the first constant-voltage step on the voltage-current characteristic (at a voltage $h f / 2 e$).

To produce a more useful formula for E , it might be assumed that $R_d \sim R$ and $R_s \sim R$ where R is the junction's normal resistance (measured at currents much greater than I_0). For niobium junctions, $I_0 R$ is about 2 mV [6], [7]. Thus, at 891 GHz, E is predicted to be about 0.1, independent of the IF used. With a preamplifier of noise temperature ~ 500 K (as was used in these experiments), the minimum detectable power would thus be about 10^{-19} W/Hz. Note that eq. (1) predicts conversion gain for sufficiently low signal frequencies, although up to now, no experimental observation of this has been reported.

3. Apparatus. — Two free-running hydrogen cyanide lasers provided the LO and signal. Each had an invar-spaced cavity for stability with varying temperature (for example, see [8]). In each laser, radiation was coupled out with a dielectric beam-divider, and the electrical discharge was operated in a steady striated condition from a stabilised current supply. The 4-metre LO laser gave about 10 mW maximum power, while the signal laser gave rather less. The gain characteristics of the lasers were such that the signal and LO frequencies could be made to differ by up to about 3 MHz by suitable tuning of the laser cavities. The 3 dB line-width of the laser emissions was about 10 kHz. Laser power was measured using Golay cell detectors together with calibrated attenuators of black polythene or perspex. The power calibration of each cell was based on that given by the manufacturer, together with an empirically determined factor to allow for deterioration in sensitivity since manufacture. Further checks on this calibration were performed by comparison with a thermopile device. In measuring power levels actually delivered to the entrance ports of the Josephson detector, errors can arise due to the lack of efficiency in radiation collection for measurement with

the Golay cell. Taking all possible errors into account, the power levels quoted should be correct to within ± 3 dB.

Two types of Nb-Nb point contacts were used, all data being taken with the contacts in liquid helium at 4.2 K. Initial experiments were carried out with simple pre-set contacts [9], [5], but with two distinct modes of use. In some experiments, the device was placed at the end of a 0.8 m long stainless steel light pipe of 12 mm diameter. The radiation from the two lasers was focussed into the entrance of the pipe with suitable lenses. One advantage of this arrangement was that the device could be operated in a standard 17 l liquid helium storage vessel which provided 4.2 K hold times of about a week. However, such a radiation transfer system is somewhat unsuitable for use with a point contact heterodyne device because the focussing, phase, and polarisation of the radiation are scrambled as a result of multiple reflections. In order to overcome these objections, experiments were also performed with the same type of junction, but with the latter mounted in a special cryostat. The helium container of the cryostat had sapphire windows which, at 4.2 K, were of low absorptivity to the laser radiation. The external cryostat windows were of polythene. This apparatus allowed radiation to be focussed directly onto the junction with a polythene lens of 90 mm focal length (see Fig. 1). The same lens was used for both LO and signal, the two beams having been made collinear with a dielectric beam divider arrangement. It was possible to rotate the junction so that the angle between the major junction axis and the direction of the incident radiation could be varied.

As would be expected, and as will be seen from the results, these pre-set junctions [9], which allow little control over the junction characteristics obtained, do not provide the ultimate sensitivity with a point contact system. To approach the ultimate performance more closely, an adjustable contact system was also tried. This was also mounted in the windowed cryostat and is shown schematically in figure 1b. The basic geometry of the junction arrangement was suggested by a system used by D. G. McDonald (private communication, but some details in [10]). The pointed side of the contact was produced by etching in a HF-HNO₃ mixture. To keep surface oxides to a minimum, the anvil was cleaned (in the same acid mixture) within a few minutes of the apparatus being placed in the cryostat and cooled. The contact was made and adjusted at low temperatures using a cantilever system which provided a fine, smooth movement (Blaney, unpublished).

With all the junctions, the usual electrical connections for monitoring and biasing were provided, and a 50 Ω coaxial cable was used to bring the IF signal to the room temperature preamplifier. In most experiments, this amplifier was an Avanteck UAA 177B with nominal gain and noise figure of

FIG. 1. — Schematic arrangement of experiments in which radiation was directly focussed onto the junctions. *a*) Focussing onto pre-set junctions. The direction of the electric field vector, E , of the radiation is shown. The cone half-angle of the pointed side of the junction was about 25° . *b*) Focussing arrangement with adjustable contacts. The hooked and pointed wire was of 0.25 mm diameter Nb. The moveable anvil was of 1 mm diameter wire. The apparatus was designed for microwave and laser mixing experiments. The junction was made across the narrow dimension of a reduced-height K-band waveguide with a 3 mm diameter hole in one of the large area walls to give access to the laser radiation. The orientation of the junction relative to the direction of the radiation was essentially fixed as shown.

40 dB and 4 dB respectively, a $50\ \Omega$ input resistance and a bandwidth from 5 kHz to 500 MHz.

4. Results. — In the following discussion, the radiation power levels quoted, except where otherwise stated, are those incident at the room temperature input port of the detector, with no correction for the inefficiency of the radiation input coupling arrangements. A detailed discussion of voltage-current (V - I) characteristics of useful junctions will be given later. No extensive measurements were carried out on junctions which did not show a clear first Josephson step (at 1.84 mV) with at most 1 mW of laser power. As regards mixing performance, few general precise quantitative conclusions are possible as behaviour varied considerably from junction to junction. However, some qualitative features were fairly generally observed, and these are described below.

A dc bias current was always required to obtain

an IF signal. An example of IF voltage amplitude as a function of bias current is shown in figure 2. The maxima in the IF voltage usually occurred at the extremities of « steps » on the V - I characteristic, and on flat (i. e. constant-voltage) steps, the signal disappeared. These maxima were usually associated with maxima in the junction differential resistance [1], [5]. (The narrow peak in V_{IF} at a bias of about $5\ \mu\text{A}$ in figure 2 is associated with such a maximum in resistance. This type of feature was observed on several occasions.) The « active » steps could be the

FIG. 2. — An example of IF voltage, V_{IF} , as a function of bias current, I_{DC} , for fixed values of LO power, P_L (5 mW) and signal power, P_S ($\sim 1\ \mu\text{W}$). V_{IF} (which includes the amplifier noise) is referred to the preamplifier input. IF $\sim 700\ \text{kHz}$, IF bandwidth 1 MHz. Adjustable junction. For higher I_{DC} , V_{IF} became smaller and junction noise began to be observed. The dc voltage-current characteristic of the junction (also shown) was plotted simultaneously: $I_0 = 50\ \mu\text{A}$, $R = 31\ \Omega$. Optimum LO power for this junction was about 0.1 mW.

usual Josephson steps, « subharmonic » steps [11], or steps presumably induced by electromagnetic resonances in the structure surrounding the junction. The amplitude of the IF signal was in general different on each of the two ends of a given step (except for the zero-voltage step). With the exception of the self-induced steps, the visible steps were produced by the LO radiation, the signal power usually being low enough that the steps created by it were virtually invisible. The bias currents giving maxima in the IF power were, of course, a function of LO power. IF power enhancement was also sometimes observed when the dc voltage was near the energy gap voltage ($\sim 3\ \text{mV}$).

Assuming the dc bias point was kept optimised, the IF level was a non-monotonic function of LO power. An example of this is shown in figure 3.

FIG. 3. — An example of IF voltage V_{IF} (in arbitrary linear units) as a function of LO power, P_L , for bias points near the zero voltage step and on the extremities of the first Josephson step at 1.84 mV. Data for an adjustable junction with $I_0 = 110 \mu\text{A}$, $R = 15 \Omega$. At each value of P_L , the bias was adjusted to maximise V_{IF} .

At the extremity of the zero-voltage step, the optimum LO power was usually much less than that necessary to produce a maximum in the width of the step at 1.84 mV. For junctions sufficiently sensitive to the laser radiation that it was possible to observe the zero-voltage step width going through a minimum and then increasing again, there were indications that the IF power also went through a minimum, although a complete disappearance of the IF level was never observed. IF signals observed on each side of the step at 1.84 mV also varied non-monotonically with increasing LO power. This variation was different for each side of the step and IF level disappearances were not obviously related to LO powers at which the step width was stationary. While the LO power experimentally available was only sufficient to drive the junction through one maximum in conversion efficiency, it is considered unlikely that higher LO powers will give rise to higher conversion efficiency. As bias points near the zero-voltage step gave the best overall conversion efficiencies, further discussion will be restricted to operation at such points.

Optimum LO power varied from junction to junction but was usually in the range 10^{-5} to 10^{-3} W, and in any case, never needed critical adjustment.

IF power varied linearly with signal power when the latter was below 10^{-6} W, although in the less sensitive junctions, this figure could be as high as 10^{-4} W. Above these limits, the IF level varied more slowly with increasing signal, and there was considerable distortion of the IF waveform (see below). The conversion efficiency of these devices was independent of the IF with the latter varied up to 3 MHz.

In most junctions, the second and subsequent harmonics of the IF were 25 to 30 dB below the fundamental. However, several junctions had bias points where harmonic content rose to about 10 dB below the fundamental. These particular bias points tended to be where the differential resistance of the junction was large over a small current range, usually with associated hysteresis on the V - I curve. These points gave somewhat unstable (although rather large) IF signals, together with noticeable junction noise. When the signal was such as to drive the junction beyond the linear response region (see above), harmonic content also increased, with the second harmonic sometimes exceeding the fundamental for some bias points.

No investigation of the noise properties of the junctions was undertaken although in the usual circumstances in which the detecting system was operated, the junction-generated noise was not readily observable when compared with that of the room-temperature preamplifier. Exceptions were when a junction was biased to an unstable hysteretic point, or if the bias current was large enough to drive the dc junction voltage to about 5 mV or more. In the latter case, the generated noise had an approximately $(\text{frequency})^{-1}$ spectrum. No particularly stringent measures were taken to protect junctions against externally generated noise. There was no evidence to suggest that noise injected into the junction had much influence on mixing efficiency, although a full investigation of this aspect would be worthwhile. The IF was usually kept above about 50 kHz and under these conditions, LO noise was not a problem with the lasers used. LO noise problems arising from the finite laser linewidth can be expected for IF's less than a few tens of kilohertz.

5. Conversion efficiency and minimum detectable power. — Once in the linear response region, the combined input signal matching and conversion efficiency could be measured. By suitable extrapolation of the IF power to the noise level, the minimum detectable power of the system was obtained. This was checked on several occasions by attenuating the signal until the power signal-to-noise ratio at the IF (as measured using a rms voltmeter with a 1 MHz bandwidth) fell to one. For each junction, these measurements were taken with the LO power, current bias and signal focus adjusted to optimise the IF level. Only stable bias points where amplifier noise predominated and IF harmonic content was relatively low

TABLE I

Junction type	Radiation coupling	No. of junctions measured	CL ^(a) dB ± 3 dB	Best sensitivity junction		I ₀ μA	R Ω
				MDP ^(c) W/Hz ± 3 dB	Optimum PL ^(d) mW		
Pre-set	Light pipe	6	56	3 × 10 ⁻¹⁵	0.5	80	16
Pre-set	Direct focus	5	48 (45) ^(b)	5 × 10 ⁻¹⁶	0.5	195	7.8
Adjustable	Direct focus	8	32 (29) ^(b)	1 × 10 ⁻¹⁷	0.1	230	9.4

^(a) Combined conversion and signal input matching loss.

^(b) The figures in parentheses are corrected to allow for the 3 dB reflection loss in the sapphire window of the cryostat.

^(c) Minimum detectable power (for a power signal-to-noise ratio of one) for a room temperature preamplifier of noise temperature 520 (± 30) K, as was used in most of the experiments. Following convention, the MDP is given for a 1 Hz IF bandwidth. This, however, is purely notional as the laser linewidth was of the order of 10 kHz. Measurements were usually taken in a 10 kHz to 1 MHz bandwidth.

^(d) The optimum LO powers are approximate and probably overestimate the required power : this is because in most cases the experiment was arranged to optimise the signal level at the detector, often at the expense of LO coupling efficiency.

(see above) were considered. No corrections were made for the mismatch of the junction to the preamplifier, although this loss was probably not more than about 3 dB for the junction resistances used.

The experimental results are summarised in table I. Although detailed sensitivity measurements were carried out on eleven pre-set junctions, an approximately equal number were rejected without full measurement because they were obviously of low sensitivity. As already mentioned, there was considerable lack of control over the junction characteristics obtained with these devices, and it was not possible to compare the performance of a single junction in both light pipe and direct focus systems. Thus, in the relatively small number of experiments performed, it was difficult to provide decisive evidence of any sensitivity advantage which one coupling system might have over the other. However, using the light pipe, the positions of the lenses used to focus both LO and signal beams into the pipe entrance required very critical adjustment and for this reason alone, the system cannot be recommended. With the direct focus arrangement, this adjustment was less critical. In the latter case, a 90 mm focal length lens focussed the signal laser beam down to a spot of approximately Gaussian intensity profile in which more than half the energy was concentrated into a disc of 1 mm diameter. For the laser beam used, this was close to the diffraction limit for a lens of that focal length. The best coupling of the radiation to the junction occurred when the incoming beam direction approximately bisected the angle between the anvil surface and the side of the cone of the junction point (see Fig. 1). The lowest conversion losses obtained are in table I : the highest such loss, obtained for pre-set junctions in both the light pipe and direct focus arrangements, was 67 dB.

As expected, superior sensitivity and better consistency was achieved with the adjustable junctions (see Table I). The same 90 mm lens was used as with the pre-set junctions. By careful junction adjustment, useful performance could be obtained on virtually every experimental run. Of the eight junctions on which full sensitivity measurements were carried out, the worst conversion loss obtained was 56 dB, but this was to some extent unrepresentative, in that in all other junctions the loss was 42 dB or less. Some of the improvement with this type of junction may be due to more favourable antenna properties than with the pre-set type. There is no reason to believe that the optimum antenna characteristics have been achieved. For example, a result better than the 29 dB conversion loss obtained (after correction for the cryostat window loss) may be possible by suitably adjusting the angle between the laser beam and the junction wire [12]. This adjustment could not be readily done with the arrangement used.

Values of I₀ and R for the junctions of best sensitivity in each type of experiment are given in table I. These parameters are far from adequate to characterize the properties of a point contact junction. A relevant discussion of the desirable properties of junctions for high frequency mixing was given in an earlier paper [5]. In the present work, junctions of resistance, R, in the range 1 to 40 Ω were used, although below 5 Ω, performance was markedly poorer. For the best few junctions (of the adjustable type), the product I₀R was about 2 mV or slightly larger. A noticeable feature on the V-I characteristic at the energy gap voltage (~ 3 mV) was desirable but junctions in which this feature was very pronounced (with a quite wide and flat « step » at this voltage) were not so good. With no incident laser power,

the transition from zero voltage to the approximately ohmic part of the characteristic was preferably larger than 0.5 mV in height, and with little or no hysteresis. Some hysteresis was permissible as this could be quenched with the LO power. In the best adjustable junctions, the « excess » supercurrent was quite small in the sense that the maximum width of the first Josephson step (at 1.84 mV) approached (i. e. was 70 % or more of) the width predicted ($1.16 I_0$) by the simple Bessel-function formulation of a junction driven from a voltage source [13]. With such a junction as this, steps up to the fifth harmonic were readily observed (i. e. without recourse to differential techniques) with the 10 mW LO power available.

6. Conclusions. — Point contact Josephson junctions have been shown to have conversion losses less than about 30 dB when used as mixers at 891 GHz with IF's near 1 MHz. This may be reduced by further improvement of the input matching conditions. If it is assumed that the observations here are due entirely to Josephson-like effects (and there is no evidence that they are not), then the IF bandwidth should extend well into the gigahertz region [14]. If a pre-amplifier of much lower noise temperature were available and assuming that LO noise did not become a problem, the minimum detectable power should be decreased, possibly by as much as 20 dB, before junction noise becomes the limitation. Although it has all the drawbacks of a point contact detector, particularly the problem of input matching of the

signal (which could be troublesome with uncollimated radiation), good design can provide acceptable mechanical stability and LO power is neither large nor critical in magnitude for optimum performance.

Comparable heterodyne detectors in this spectral region are those based on free electron absorption in cooled semiconductors (see, for example [15]), or the room temperature metal-semiconductor or metal-metal point contact diodes (for example [16], [17]). The former may have conversion efficiencies comparable with the Josephson devices although the useful IF bandwidth is only about 10 MHz [15]. The room temperature diodes have IF bandwidths well into the gigahertz region, but no comprehensive measurements of conversion loss near 1 THz are presently available.

The lack of convenient tunable LO's in the sub-millimetre region largely restricts these detectors to use with lasers (e. g. in plasma diagnostics). This LO problem may be solved by harmonic generation (in the junction) of tunable microwave sources.

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