COMPARATIVE PERFORMANCE OF HgCdTe PHOTODIODES FOR HETERODYNE APPLICATION

Herbert R. Kowitz
Langley Research Center

SUMMARY

Photodiodes are used as optical photomixers in Laser Heterodyne Spectrometers (LHS) systems to enable high resolution spectroscopy. A very important parameter in any photomixer application is the photodiode's quantum efficiency because of its direct effect on the system's signal-to-noise ratio. Quantum efficiency, however, is usually specified by photodiode manufacturers as the direct current (dc) quantum efficiency. It is important for the LHS application to determine if the quantum efficiency differs for the heterodyne mode of operation and by how much. This paper describes the measurement techniques used by the LHS Conceptual Design Team (CDT) to determine photodiode dc and heterodyne quantum efficiencies. The theory behind these measurements as well as actual measurement data for two currently available HgCdTe photodiodes are presented.

DC QUANTUM EFFICIENCY

The dc quantum efficiency of a photodiode represents a figure of merit of how well the device converts light energy into electrical energy or, more specifically, how many amperes of photocurrent are generated for each watt of optical signal power. The response (R) of a photodiode in amperes/watt is given by

$$R = \eta_{dc} \left(\frac{q}{hf}\right) \tag{1}$$

where:

η_{dc} = dc quantum efficiency
q = electron charge = 1.602 (10^{-19}) Coulombs
h = 6.625 (10^{-34}) Joule-sec
f = 3 $(10^{14})/\lambda$ with the wavelength (λ) expressed in microns

As can be seen by equation (1), the theoretical response is maximum for 100 percent dc quantum efficiency. At a wavelength of 10.6 microns, the maximum response is 8.544 amperes per watt.

The dc quantum efficiency of a given photodiode can be determined by measuring the photocurrent generated for a given signal power impinging on the photodiode's sensitive area. The difficulty (and any possible inaccuracy) lies in the determination of the factors that influence the amount of signal power. The measurement set-up that was used for photodetector response measurements (see fig. 1) consists of a blackbody radiation source, an optical filter, and focusing mirrors. This set-up was part of an overall LHS layout and not optimized for photodetector response measurements. The chopper and the beam splitter are not required for the dc measurements, but are needed for heterodyne measurements discussed later in this paper.

The blackbody emittance (N_λ) is given by

$$N_\lambda = \frac{c_1 d\lambda}{\pi\lambda^5[\exp(c_2/\lambda T) - 1]} \quad \frac{\text{watts}}{\text{cm}^2 \cdot \text{ster}} \tag{2}$$

where c_1 is 3.7405 (10^4) and c_2 is 1.4388 (10^4) if the wavelength is expressed in microns and the blackbody temperature (T) is in degrees Kelvin. The tests were conducted at 10.6 microns with a 0.3963 micron optical filter resulting in a radiance of 1.866 (10^4) watts/cm$^2\cdot$ster for the 1273 K source.

The optical power at the detector is related to this radiance by

$$P_{det} = N_\lambda \tau_{CH} \tau_F (\tau_M)^3 \tau_{BS} \tau_{POL} \frac{\pi}{4} \left(\frac{d}{\ell}\right)^2 A_{det} \cos\theta \text{ watts} \tag{3}$$

where:

τ_{CH} = chopper factor = 0.5

τ_F = filter transmission factor = 0.65

τ_M = mirror transmission factor = 0.97

τ_{BS} = beam splitter factor = 0.5

τ_{POL} = polarization factor = 0.5

d = lens diameter = 5.0 cm

ℓ = focal length = 15.2 cm

θ = off normal detector mounting angle = 30°

A_{det} = detector area = 1.21 (10^{-4}) cm^2 for unit (A)
= 1.7 (10^{-4}) cm^2 for unit (B)

Using these given factors in equation (3) results in optical powers of 0.0123 microwatts for unit (A) and 0.0173 microwatts for unit (B). These powers differ because detector (B) has about 40 percent greater sensitive area. To assure a valid comparison the detectors have to be overfilled. This condition was verified by transverse movement of the photodetectors without loss of photocurrent. The measured photocurrents were 0.05 and 0.1 microamperes for detectors (A) and (B), respectively. Application of equation (1) results in η_{dc} = 48 percent for detector (A) and η_{dc} = 68 percent for detector (B).

HETERODYNE QUANTUM EFFICIENCY - THEORY

The heterodyne quantum efficiency is more difficult to ascertain because it involves the heterodyne mode of operation, i.e., the mixing of two optical signals to obtain a "beat signal" in the microwave frequency range. The test set-up used for the heterodyne efficiency measurements (see fig. 2) consists of a blackbody source, a 50 percent duty cycle chopper, focusing optics, and a 50/50 beam splitter to combine the signal (blackbody) with the local oscillator (CO_2 laser). The RF portion consists of a 5 to 550 MHz preamplifier, a 10 to 115 MHz amplifier, and a square-law detector to detect the heterodyne signal power in the midband frequency range (10 to 155 MHz). The detector output is then synchronously demodulated and filtered by a running-mean integrator whose value is read at a 1-second integration time and reset to zero. The chopper rate was chosen to be 1024 Hz to simplify the generation of the required control pulses.

The scheme followed to obtain a heterodyne quantum efficiency measurement is similar to the dc quantum efficiency measurement except that for the heterodyne case, the measured signal-to-noise ratio (SNR) is compared to the maximum theoretical obtainable SNR.

The SNR for the described implementation is given by

$$\mathrm{SNR} = \frac{4\,\eta_{Het}\,q\,I_{ph}\,t}{\left[\exp(hf/kT) - 1\right]} \cdot \frac{\sqrt{B_{IF}\tau}}{(F-1)\dfrac{kT_o}{R_{11}} + 2q(I_{ph} + I_d)} \tag{4}$$

where:

η_{Het} = heterodyne quantum efficiency
I_{ph} = signal induced photocurrent
t = optical transmission factor = 0.093
B_{IF} = IF bandwidth = 105 MHz
τ = post detection integration time = 1 sec
F = noise factor of preamplifier = 1.58 (NF = 2 dB)
T_o = 290 K
R_{11} = equivalent input impedance of preamplifier
I_d = dark photocurrent

As can be seen by equation (4), the SNR is directly dependent on the photodiode's heterodyne quantum efficiency. It should be noted that the optical transmission factor has the same impact on the system SNR as the quantum efficiency indicating that both factors should be maximized. An increase in the IF bandwidth or the integration time, however, has less effect; doubling either only results in a 41.4 percent improvement in the signal-to-noise ratio. Also, integration time is mission dependent and cannot be arbitrarily increased except for static measurements (as in the lab). The IF bandwidth is limited by two factors: (a) the photomixer's own frequency response limitation, and (b) the increased noise factor of wide bandwidth preamplifiers.

Other important factors that influence the SNR are the temperature of the blackbody source and the effective temperature of the noise sources operating in the LHS system. The blackbody source temperature affects the SNR via the $[\exp(hf/kT) - 1]^{-1}$ factor of equation (4). For example, at 10.6 microns the SNR increases by a factor of approximately 7 when considering the blackbody temperature of the sun at 5600 K versus the temperature of 1273 K of the laboratory source.

The noise sources operating in a LHS system are basically Johnson noise referred to the input of the preamplifier and photodiode shot noise. Their effects are accounted for by the $(F - 1)kT_o/R_{11}$ and $2q(I_{ph} + I_d)$ factors, respectively. Because an unstable reference source will cause an apparent noise component as well, a CO_2 laser was chosen as the local oscillator for the heterodyne quantum efficiency measurements.

HETERODYNE QUANTUM EFFICIENCY MEASUREMENTS - MIDBAND

The heterodyne quantum efficiency measurements for the midband case were conducted in the 10 to 105 MHz frequency range (determined by the amplifier bandwidth of the AIL 2392C radiometer of fig. 2) to assure that the measurement is within the photodetector response bandwidth. It should be noted that the test set-up was part of an overall optical layout for the LHS system and was not optimized for photomixer response measurements. The inability to determine the exact transmission factors, therefore, will cause errors in the absolute measurements, but should be more than adequate for determining heterodyne frequency response rolloff. The SNR was measured by using a microprocessor controlled digital voltmeter (DVM) to measure the average of the RF detector output voltage (1 second integrator) and its standard deviation. The measured SNR was determined as follows:

$$SNR = \frac{V_{LO+BB} - V_{BB}}{\sigma} = \frac{V_{HET}}{\sigma} \tag{5}$$

where:

V_{LO+BB} = average detected output with the CO_2 laser and BB heterodyning
V_{BB} = average detected output with the CO_2 laser path blocked
σ = standard deviation of detected output during heterodyning
V_{HET} = heterodyne signal output

The SNR was measured for photocurrents up to about 1 milliampere. The test results are provided in table I for both available photomixers. It should be noted that the photocurrents shown are above the photomixer dark currents. Table II depicts the parameter values used and the theoretical SNR calculation results. It should be noted that for photomixer (B), the dark durrent parameter value used in the theoretical SNR calculations was about 50 percent of the measured dark current because it was found that only about half of the dark current for this photomixer contributed to shot noise. This phenomenon needs further investigation but is outside the scope of this paper. Figure 3 shows both the measured and the calculated values for the SNR in the 10 to 115 MHz band. A comparison between the theoretical and the measured SNR's results in heterodyne quantum efficiencies of 16.5 percent for photomixer (A) and about 62 percent for photomixer (B).

HETERODYNE QUANTUM EFFICIENCY VERSUS FREQUENCY

The quantum efficiency for photodiode (A) decreased from 48 percent at dc to 16.5 percent in the 10 to 115 MHz band and photodiode (B) decreased from 68 percent to 62 percent. This prompted implementation of the test set-up shown in figure 4 to enable a heterodyne frequency response check. The results of these tests are shown in figure 5 for photomixer (A) and in figure 6 for photomixer (B). Because the dc response cannot be obtained with this test implementation, no direct comparison to the dc quantum efficiency can be made. Also, this implementation introduces its own signature on the overall frequency response because of VSWR, amplifier in-band ripple, and RF mixer response effects. These effects have been "backed out" resulting with the corrected response curves shown in figures 5 and 6. It is seen that photomixer (A) has a roll-off in the 10 to 110 MHz band that is not as pronounced for photomixer (B). Photomixer (A) appears to be at its half power point at about 450 MHz. Photomixer (B) has not approached its half power points at the 500 MHz limitation of the test set-up and requires a wider bandwidth implementation to investigate.

CONCLUSIONS

Photodiodes used as photomixers in LHS systems exhibit quantum efficiencies in the heterodyne mode of operation that are lower than their dc quantum efficiencies. Also, this heterodyne efficiency is not constant over the photodiodes specified bandwidth, but exhibits a gentle roll-off with frequency. Consequently, photodiodes that are to be used in heterodyne applications should be tested in that mode and a minimum heterodyne quantum efficiency specified at the upper frequency of interest. These tests require much care, however, due to the signature of the RF components in the test setup.

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TABLE I.- SNR MEASUREMENTS (MIDBAND)

	I_{ph}*	$V_{LO} + V_{BB}$	V_{BB}	σ	SNR
Photo-mixer (A) *I_d = 38 μa	124 μa	1.11 V	0.688 V	0.0087 V	48.5
	209	1.487	0.688	0.0097	82.4
	276	1.55	0.645	0.0116	78.0
	298	1.539	0.641	0.0096	93.5
	409	1.73	0.614	0.0085	131.3
	603	2.063	0.615	0.0114	127.0
	833	1.967	0.54	0.0109	130.9
	1034	2.182	0.538	0.0113	145.5
Photo-mixer (B) *I_d = 375 μa	60	1.72	0.86	0.0118	72.9
	105	2.06	0.80	0.0103	122.3
	210	2.87	0.74	0.0108	197.2
	335	3.49	0.70	0.0082	340.2
	445	4.14	0.69	0.01	345.0
	575	4.26	0.65	0.0087	414.9
	655	4.64	0.65	0.0096	415.6
	900	4.99	0.614	0.01	437.6
	1020	5.30	0.61	0.0098	478.6

TABLE II.- SNR CALCULATIONS

PARAMETER	DET. (A)	DET. (B)	I_{ph}	SNR (A)	SNR (B)
BB Temperature (K)	1273	1273	100 μa	88	170
η_{HET}	0.25	0.75	200	130	277
t	0.093	0.093	300	155	351
NF (dB)	2.0	2.0	400	171	404
R_{11} (ohms)	50	50	500	183	447
Dark Current (μa)	38	195*	600	191	478
B (MHz)	105	105	700	198	504
τ (sec)	1.0	1.0	800	203	525
			900	207	543
			1000	211	559

*Portion of 375 μa dark current that contributes to shot noise.

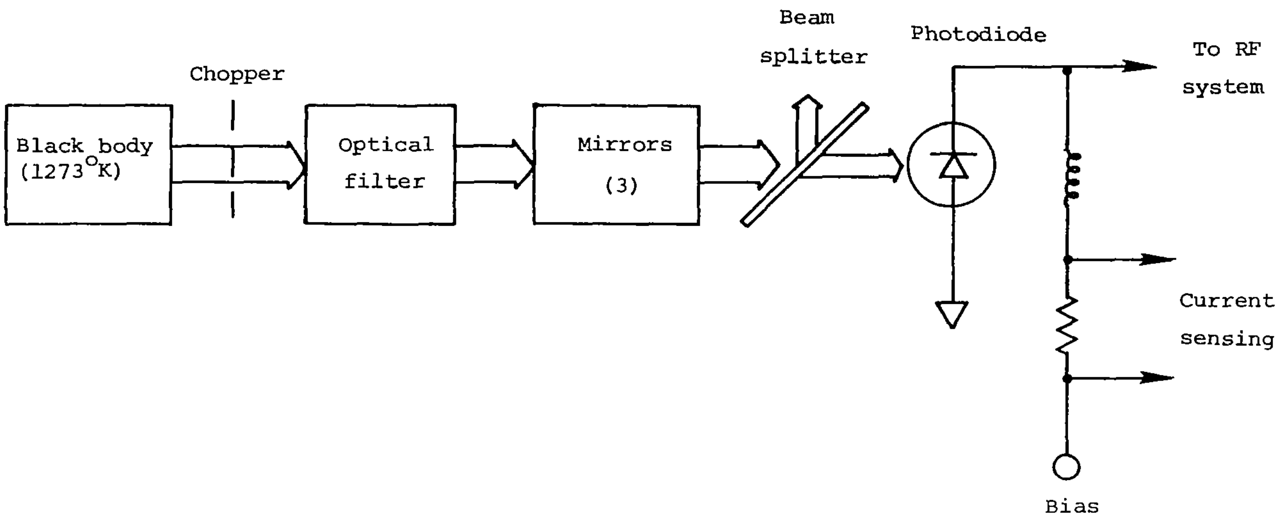
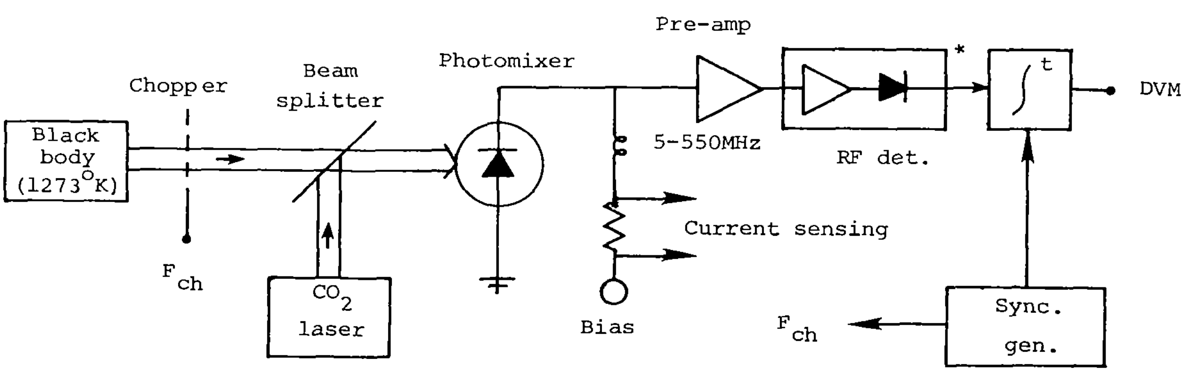


Figure 1.- Photodetector dc response test.



* Portion of AIL type 2392C radiometer: BW = 10 to 115 MHz

Figure 2.- Photomixer heterodyne response test set-up.

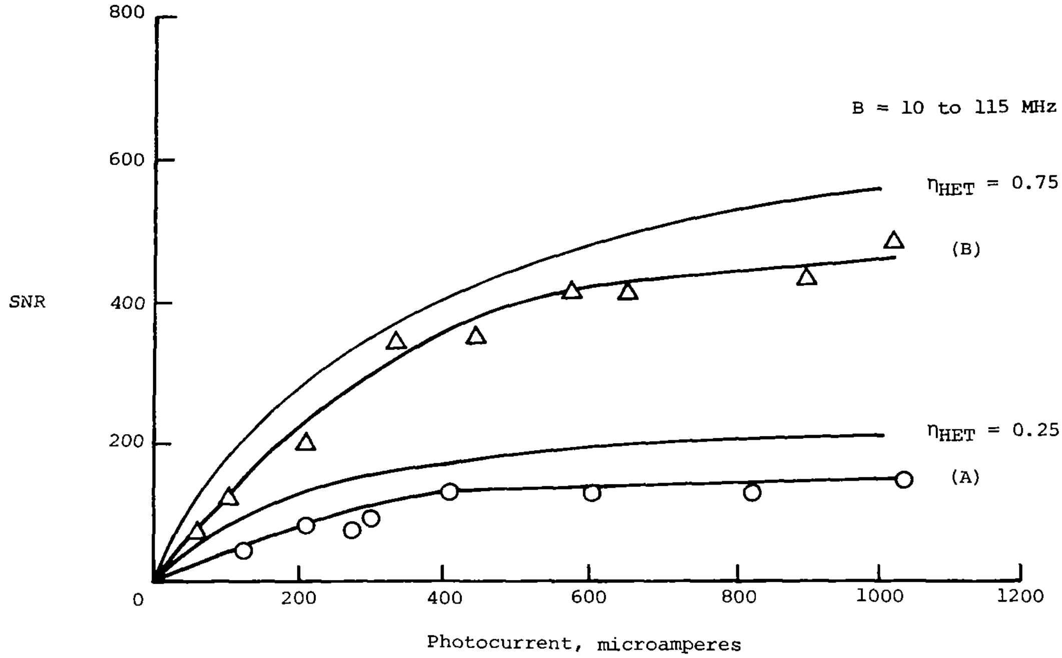


Figure 3.- Measured versus theoretical SNR.

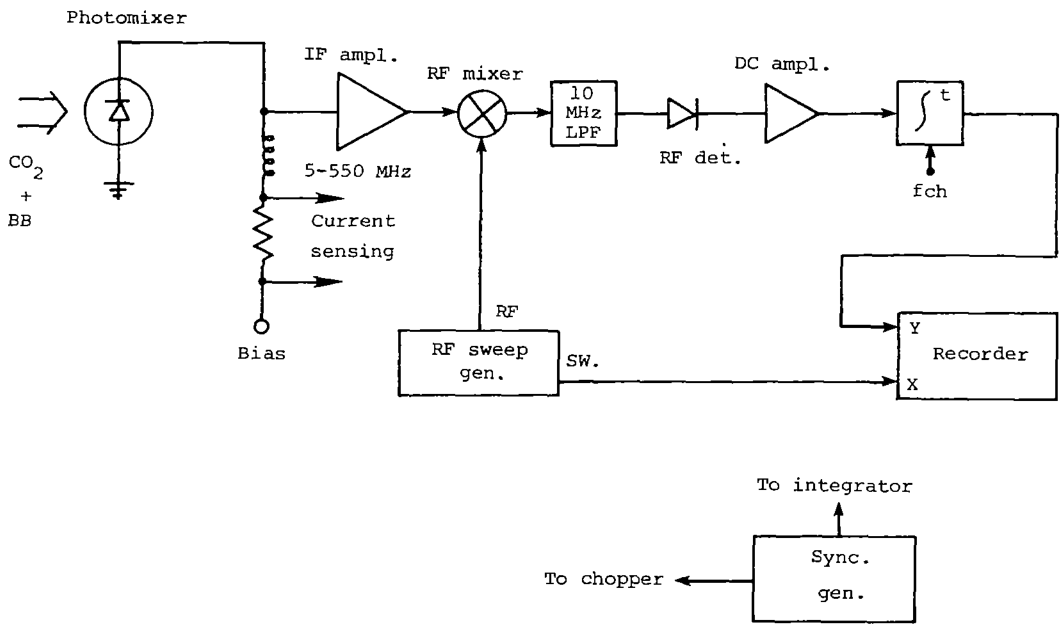


Figure 4.- Swept frequency response test set-up.

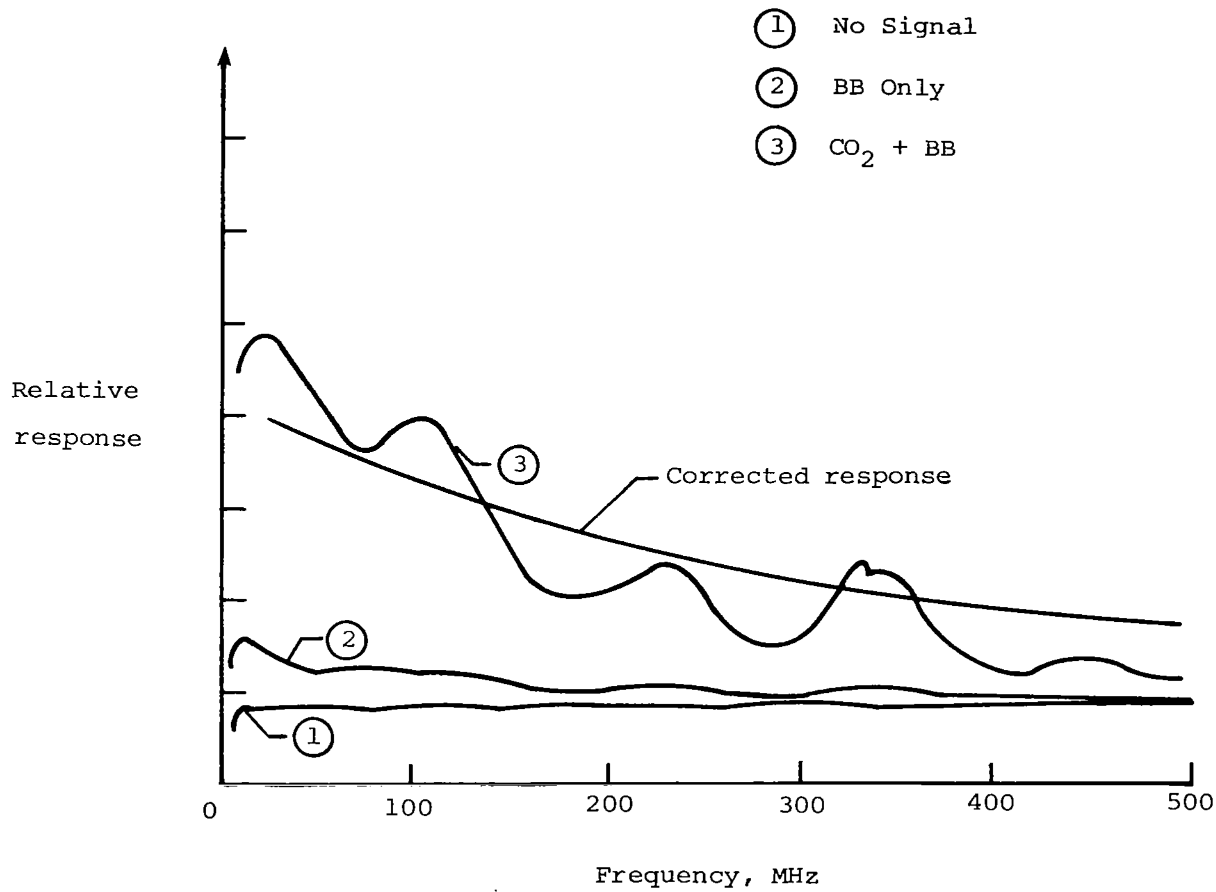


Figure 5.- Photomixer (A) response - 300 μα.

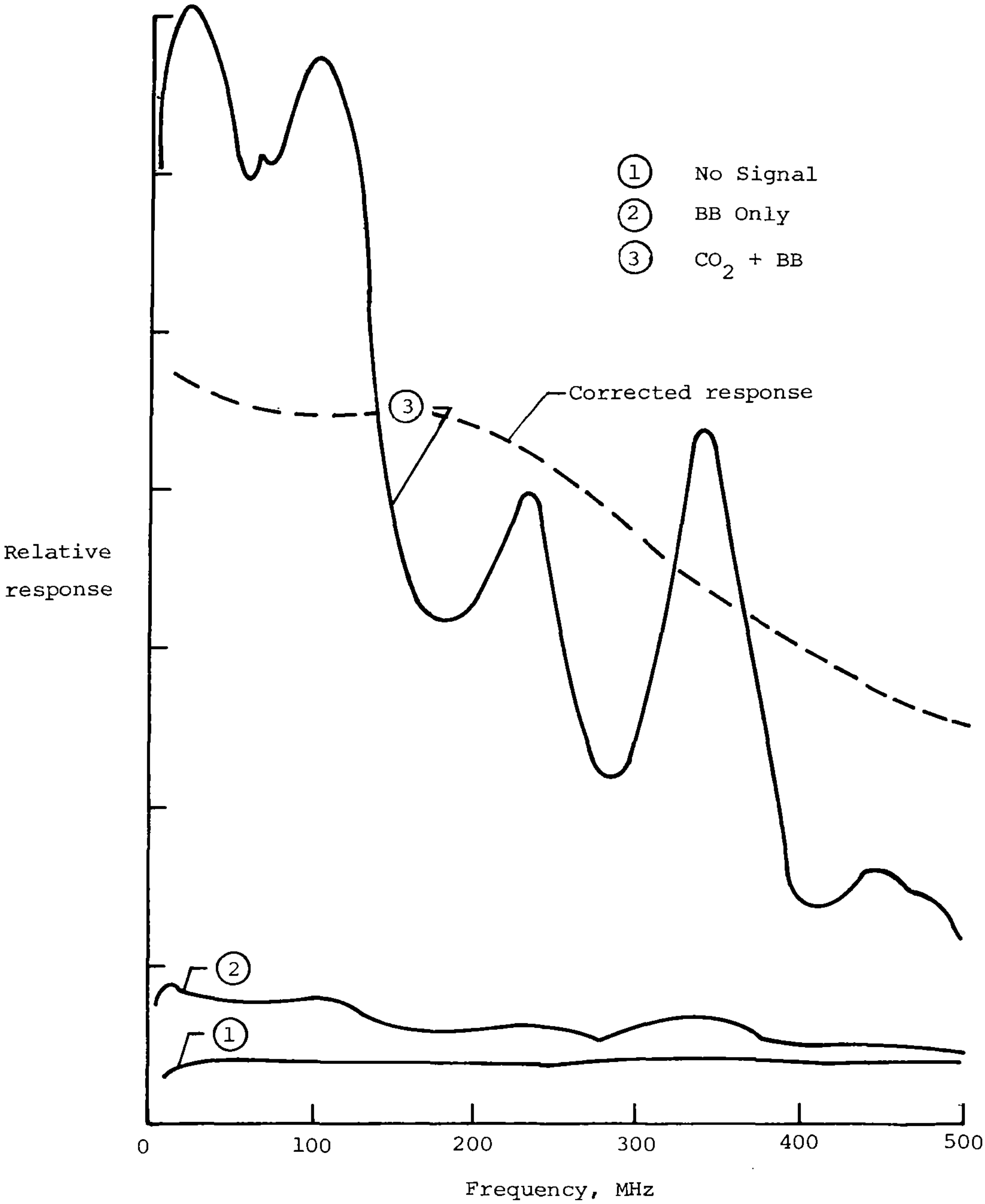


Figure 6.- Photomixer (B) response - 300 μα.